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VOL. I

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PRESIDENTIAL ADDRESS

By Mr. W. H. E. Thornthwaite, F.R.A.S. (*President, 1899*).

Delivered at a Meeting of the Optical Society on October 26th, 1899.

WHEN, at the request of the Committee that I should give an inaugural address, I considered the selection of a subject connected with the science of optics, two important but very different factors presented themselves:—The immensity of a subject of such infinite variety, and the extent of the other business to be transacted this evening. I decided, therefore, that a short and general address would best meet the case.

We do not yet thoroughly understand the nature of light or even if the corpuscular or undulatory theory is absolutely the correct one, though the latter is now universally received. Even about some of the properties of light we know but very little. Such knowledge must, indeed, be infinite. For example, we are told that the brightest light which exists we may have never seen, as, though it has been travelling at the rate of 186,000 miles per second, the light of some fixed stars may not yet have reached the earth; and yet beyond these stars there is still infinite distance. The mind of man fails to grasp such facts, and, of course, no telescope, however powerful, is of any assistance in magnifying light which is utterly beyond human vision. The light coming from the ultra-violet rays of the spectrum or from the Röntgen rays, is also invisible and only proves its existence by its marvellous effects. On the other hand there are beauties in Nature so minute as to be equally beyond the power of any microscope to resolve.

Though the nature of light is even now not fully understood, many of its properties were investigated in very early days. Aristotle, several hundred years before the birth of our Lord, tried to solve the question, "Why cannot we see in the dark?" our rather, "What is darkness?" The laws of reflexion were understood before those of refraction, the former being found by the observation of objects when reflected from the surface of water or burnished metal; the latter from the magnifying and displacing effects noticed when objects are viewed through transparent vessels filled with fluid, to which allusion is made by Pliny. In the first century Cleomedes noticed that a coin placed at the bottom of

a cup appeared to rise as water was poured in, and about the same date Ptolemy discovered atmospheric refraction and wrote his great work on optics, treating of both refraction and reflexion. About the time of the Norman Conquest, El-Hasan was the earliest philosopher to give a reasonable description of the anatomy of the eye and of the optical principles of vision. Since then optics has been the study of every eminent scientific man; I specially mention the following:—Roger Bacon, who is said to have invented convex spectacles, though probably they were used much earlier; Kepler and Galileo; Huyghens, who discovered polarisation, and Cassini; Newton, the author of the great "Principia," but a supporter of the corpuscular theory with Laplace; Römer, who discovered the velocity of light in 1676, and first used the transit instrument; Bradley, who discovered the aberration of light; Dolland, Herschel, Fresnel, who discovered the true theory of diffraction; Young, who discovered the undulatory theory; Fraünhofer, Littrow, Brewster, Airy, who first corrected astigmatism; Foucault, Abbe, Donders, Crookes and Lord Rayleigh, not to mention the able Vice-Presidents of this Society, who have done so much to advance the application of optical science in various directions.

To allude to a tithe of the wonderful optical instruments these eminent men have invented and improved would take a very long time, and I would only select the few which are figured in the margin of the diploma of the Spectacle Makers Company. Where would medical science, histology, and biology be without the aid of the microscope? Has it not been the means of explaining to us the principles of generation, circulation, and bacteriology? Does not the telescope enable us to take time to the fraction of a second by means of the transit star? How the addition of a telescope has improved the accuracy of the sextant and other mathematical instruments? How many new metals, new elements, have been discovered by means of the spectroscope? How, but by the help of this instrument, could we analyse things which we can see but not handle, and so discover the composition of the sun, fixed stars, and nebulæ? Then, most wonderful of all lights, we have a light that we can only detect by its shadows, whose depth constitutes an invaluable guide to the military surgeon and enables him by means of the x or Röntgen rays to localise the position of bullets without the painful operation of probing. The practical utility of Sir William Crookes' radiometer has yet to be proved, but at least it has demonstrated that light can be a source of motive power without cost!

I might refer to other optical instruments, such as the camera, and

Nature's camera, the eye, with its iris diaphragm, its focusing screen and its wide angle single lens evidencing so little aberration, either chromatic or spherical; and also to the many optical instruments which are employed to test, improve and correct vision; but I forbear and, with the very best wishes for the success and development of the Optical Society, and an earnest hope that its members will follow the lead of the eminent men I have alluded to, and also will honour the discussions of the Society by papers describing inventions of equal scientific interest and value, I conclude.

OPTICAL STANDARDS.

Paper by Mr. Lionel Laurance, *Member.*

Read before the Optical Society on December 21st, 1899.

MR. PRESIDENT and gentlemen: I feel that your committee has conferred upon me a great honour by their invitation to become the author of the first paper read before you. The selection of a suitable subject caused me considerable anxiety, but since I can hardly hope that this paper will be altogether worthy of the occasion, I ask for, and trust that you will extend to me your indulgence for any shortcomings in style and matter.

The subject selected is Optical Standards, and it therefore offers no pretence to being immediately instructive. It is intended rather for the purpose of promoting discussion—let us hope, not a heated discussion—which may ultimately prove of benefit to the optical industry.

The utility of standards in all industries has long been recognised and they are no less necessary in the optical than in any other trade, whether they be standards of measurement, of size, of quality or of design.

There is a real necessity for standardising many of the data connected with the every day requisites of the up-to-date retail Optician, so that, without burdening orders with too many details, his exact wants may be supplied without undue chance of error. Four subjects are touched upon in this paper. They are: The calibration of lenses and frames, angle notation, colour standards, and spreads of bridges.

The advanced system of optical trading, as regards spectacles and eyeglasses, consists principally in fitting to each customer a particular frame with particular lenses, exactly suited to his requirements, the ordering of which involves a mass of minute details; and a system of standards must reduce the time and labour that have to be expended on each transaction. But independent and individual standards are next to useless; to attain the full measure of utility, such must

be universally adopted by all manufacturers and by all their customers.

For example, if an Optician knows that eyes of certain calibre will serve the purpose for which the spectacle is required, he need neither take nor give the exact details of length and depth, nor need a work man spend unnecessary time in construction to dimensions given; eyes of such calibre can be kept in stock by the wholesaler and supplied at once as required.

At present the calibration of the eyes of spectacles, the angle notation of cylindrical axes, the numeration of colours and the nomenclature of bridges, as employed by each wholesale house, are without regard to any general system; so much is this the case that, if a retail Optician does not wish to incur chances of delay and loss, he must be provided with the special prescription form, the catalogue, the sample set of coloured glasses and the spread rule made by a particular house, before he dare order from it a pair of tinted sphero-cylindrical lenses in a certain sized frame.

Of course there is a point in every line of manufacture where a standard size or design does not adequately satisfy requirements, and a special pattern is wanted; but in the vast majority of cases the "standard" serves, and the "special" is needed only occasionally.

If standards are appropriate and correct, very frequently indeed the articles made to them are not only cheaper, but more efficient and more attractive than specially designed ones. It is not necessary in this paper to dilate upon the close connection that exists between standardisation and the employment of machinery in manufacture, the latter tending so greatly to the development of the trade by the production of efficient goods at reasonable prices.

Angle Notation.

The subject of standardising angle notation, as regards the setting of the axes of cylindrical lenses, is one that may be considered first. It is needless to attempt to show how many ways there are of indicating the position of a cylindrical axis; usually that employed by an Optician follows the notation of his own trial frame or that of the prescription form that a particular Oculist happens to use.

Nor do the notations of the trial frame and the prescription form always correspond; consequently, he may have to make a calculation when transferring results obtained from the one to the other. The

calculation may indeed be quite easy, but the act remains that unnecessary work has to be done.

So great is the uncertainty of numeration alone, as numeration now obtains, that Oculists generally mark on their prescriptions the cylindrical axis as being so many degrees up or down and out or in, nasal or temporal, which indication of the position of the axis is so very definite that it cannot be interpreted in any but, say, four different ways. The chances of error are, it is true, minimised if an oblique stroke accompanies the indicating number, but even then, say, 40° down and out indicates a direction so nearly midway between the horizontal and the vertical that there may still be doubt whether the 40° out is to be measured from the former or from the latter, and strokes to indicate the position of the axes cannot well accompany speech, nor be transmitted by telephone or telegraph.

The suggested system of standard angle notation is that of numbering from zero on the right hand side of the eye, as it faces the Optician and proceeding upwards, the eye being that of a human being, of a trial frame or of a spectacle. There are two reasons why this notation is superior to any other.

First, it is the ordinary trigonometrical notation of angles, and second, it is already the standard in Canada and in the United States, no other being there used. Also to a certain extent, it is the standard in India, Mexico, Central and South America, the West Indies and Australia. Optical prescriptions ought to be capable of correct interpretation in any country, no matter where written.

It is so far the only method that is recognised even in England as being, to some extent, the standard, inasmuch as it does not need to be accompanied by explanatory words or lines. And thanks to its having been adopted by our trade organ, THE OPTICIAN, many Opticians know at once what is meant by, say, 80°, without reference to any particular trial frame or special prescription form.

It is necessary to be quite clear as to what is meant by right and left in optics. By the right or the left eye of a frame, we mean that which is intended for the corresponding eye of the customer, and here no error can arise. But when we refer to the right side of an eye, we indicate that which is opposite to the Optician's right hand, and therefore here the expressions right and left differ from the medical and optical points of view.

In medical phraseology, "right" and "left" refer to the right and left of the patient, while in optics, these terms are used rather in a mathe-

matical sense, right and left being respectively to the manipulator's right and left hands.

If the numbered arc is on the upper part of the trial frame or prescription form, the notation commences, as stated, with zero on the Optician's right of each eye, that is, on the nasal side of the right eye and on the temporal side of the left eye, and proceeds upwards towards the vertical, which is 90°, and then downwards to 180°. If the numbered arc is below, the notation starts at zero to the left, that is on the temporal side of the right and on the nasal side of the left eye, and proceeds downwards over towards the right. The notation is the same for both eyes.

It is of great importance that a particular starting point for the notation should be fixed, but it is of even greater importance that the two eyes should be similarly numbered. Four reasons for this can be given :—

First. In conversation or writing, if a certain meridian, say 40°, is mentioned, it conveys to the mind of the hearer or reader a definite idea of the indicated position from an optical point of view.

Second. A certain lens, say, + 2 sph. ⌒ + 2 cyl. ax. 40°, No. 4 calibre, can be ordered by card or telegram without the necessity of stating whether it is for the right or for the left eye. In telegraphing, this is a decided advantage.

Third. In retinoscopy, when a movement of the shadow along a certain oblique meridian is mentally interpreted, one has not to consider whether it is at 120° or at 60° according to whether it is in the right or the left eye.

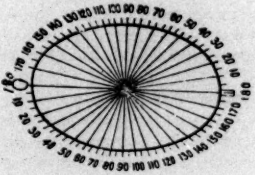
Fourth. Astigmatic charts, inclinometers, ophthalmometers and other optical instruments need but a single notation when it is similar for both eyes ; if different, the instrument must be doubly graduated, once for the right and once for the left, unless indeed a separate instrument is provided for each eye.

Take, for instance, the Maddox axis finder ; when different notations are employed, the user has not only to consider whether he has located the meridian of greatest or that of least refraction, but also whether he has the numeration of a right or of a left eye to deal with.

Suppose an Optician wishes to mark down the exact axial meridian of a single lens, say, + 1 sph. ⌒ + 1 cyl. ax. 30°. If the so-called symmetrical notation is employed, he must write, that if the lens be for the right eye, and the cylindrical to the front, it is axis 30° ; if the spherical is to the front, it is axis 150°. But if the lens be for the

left eye, then it is axis 150° if the cylindrical is to the front, and 30° if the spherical is to the front. Let us try to do away with as much uncertainty and useless labour as possible. A standard notation similar for both eyes is a necessity among advanced and accurate Opticians.

The suggested notation for both eyes is here illustrated.



Another angle notation which is sure to be suggested is that which commences at zero for both eyes, either on the nasal or on the temporal side. The principal, in fact the only, argument in its favour is that its numeration is symmetrical in respect to the middle line of the face, in the same way as astigmatism; the meridians of greatest and of least refraction in both eyes being generally, when oblique, similarly inclined towards or away from the nose. But no real advantage accrues from the adoption of such a notation.

If the proposed standard be adopted every Optician will know that two such inclinations as, say 75° in the one and 105° in the other eye are symmetrical as regards the medial line.

If possible there should be in optics no departure from mathematical procedure; and this is maintained when the angle notation for both eyes is similar to the ordinary notation of angles in trigonometry.

Spread Rules.

The diversity in spread rules, both as to the dimensions of the spreads and their numeration or lettering, illustrates how successfully we can import confusion into a very simple matter. Each spread rule is, as a rule, altogether useless except when ordering from the house by which it was supplied.

The height and set in or out, with the other needful dimensions, suffice in most cases when ordering a frame; but when the number of a

spread is given, it should be capable of correct interpretation by any one in the optical trade, just as much as the height of the bridge or the interpupillary distance.

It seems as if there could be no very scientific basis for standards in spreads of bridges; it is merely a question of obtaining a sufficiently varied series suitable for the different shapes of noses the Optician meets with in his practice.

Let the spreads be indicated by numbers 1 to 9, and let each spread be made 1 cm. deep; standardisation consisting of a definite width being given to each spread at 2 mm. and at 7 mm. from the vertex of the arch. Measurement of the width of the bases themselves would be too indefinite for standards.

Starting with No. 1, which has a width of 5 mm. at 2mm. from the vertex of the arch, and a width of 7 mm. at a distance of 7 mm. from the vertex of the arch, the spreads increase regularly by 1 mm. at the higher and by 2 mm. at the lower position, up to widths of 13 and 23 mm. This seems to be simple enough at any rate.

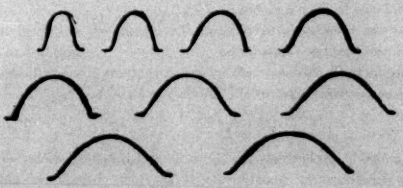
TABLE I.

Following is the suggested list.

Spreads 1 cm. in depth.

No.	Width 2mm. from the Vertex	Width 7mm. from the Vertex.
1	5mm.	7mm.
2	6mm.	9mm.
3	7mm.	11mm.
4	8mm.	13mm.
5	9mm.	15mm.
6	10mm.	17mm.
7	11mm.	19mm.
8	12mm.	21mm.
9	13mm.	23mm.

Some rough cuts showing the actual dimensions, are here shown.



Calibration of Lenses and Frames.

For the standardisation of the calibration of lenses and the eyes of spectacles, any truly scientific basis also does not seem to be possible. Here arise questions of appearance, of custom and of commercial expediency.

Most of the leading wholesale houses in the trade were—for the purposes of this paper—asked for the loan of a set of calibred lenses such as they ordinarily manufacture or sell; many of them courteously responded. It was found—notwithstanding that the indicating letters or numbers often varied—there were many of the most useful sizes common to almost every house. Thus, for instance, the No. 7 of Messrs. A, the No. 2 of Messrs. B, the No. F of Messrs. C, and the No. 14 of Messrs. D, were exactly alike in their dimensions.

It is almost unnecessary to point out that the standardisation of certain sizes in frames and lenses does not in any way affect the manufacture or sale of special lines by any individual house. Each manufacturer could still make, if he found it convenient or advisable, particular styles of spectacles and pinces-nez whose calibration varied from the standards adopted, and in addition might keep and supply such lenses and frames, interchangeable with those sold by other dealers.

Since the wire of the eye of a spectacle "gives" to a certain extent, a certain sized spectacle eye can be fitted with several lenses whose two diameters differ from one another; only in all cases, the perimeter of the lenses must be equal to the measurement of the inside of the eye wire.

Therefore, in order to standardise lenses and eye pieces of frames, we must take the circumferential measurement and not the two diameters of an oval; thus allowing various forms of lenses to be equally standard on the basis of a given circumference of a circle.

There being certain sizes in lenses and eye pieces common to most of the leading wholesale optical trade, it was not difficult to decide on the standards to be suggested.

These universal sizes to which uniform numbers are given form the basis of the proposed standards.

Taking certain calibred oval lenses in common use by the trade, the two diameters were measured. From the formula

$$r = \sqrt{\frac{a^2 + b^2}{2}}$$

where a and b respectively are the long and the short diameters of the ellipses which are the usual ovals of spectacle lenses, we obtain the

perimeters of these. And giving numbers 1 to 9 to them, they are suggested as the standards which should be adopted. No. 6 was the largest size measured, but the scale is made for the three larger sizes in order to complete the series.

TABLE 2.

The following table gives approximately the circumferences and diameters of the lenses and eye wires most commonly used in the trade.

No.	Circumference in mm.	Diameter of Circle in mm.
1	92	29·25
2	95	30·25
3	97·5	31
4	102·5	32·5
5	106·5	34
6	113	36
7	117	37·25
8	129·5	41·25
9	135	43

Now, having the above data to work upon, in order to produce, as standards, certain oval lenses which would be properly graduated, a convenient value was given to one of the two diameters required and the other was found by calculation.

Since $\pi \sqrt{\frac{a^2 + b^2}{2}} = \text{perimeter}$

it follows that $\sqrt{2\left(\frac{\text{perimeter}}{\pi}\right)^2 - a^2} = b$

Starting at 33 mm. for the long diameter in the one scale and at 35 mm. for the long diameter in the other, and increasing these lengths regularly, we obtain the following dimensions for a standard set of short oval and long oval lenses. And to make the table complete, there has also been obtained by direct measurements the sizes of a set of round oval and pantoscopic lenses, whose perimeter is, in each case, the same as that of the corresponding number of a circular and of an elliptical lens.

TABLE 3.

The proposed complete set of standard calibres for lenses and eye wires is as follows:—

No.	Cir.	Dia.	Short Oval	Long Oval	Round Oval	Panto.
1	92	29·25	33 by 25	35 by 22	32 by 27	34 by 24·5
2	95	30·25	34 by 26	36 by 23	33 by 28	35 by 25·5
3	97·5	31	35 by 26	37 by 23·50	34 by 28	36 by 25·5
4	102·5	32·5	36·5 by 28	38·5 by 25·25	35·5 by 30	37·5 by 27·5
5	106·5	34	38 by 29·25	40 by 26·50	37 by 31	39 by 28·5
6	113	36	40 by 31·50	42 by 28·75	39 by 33	41 by 30·5
7	117	37·25	42 by 31·75	44 by 29·75		
8	129·5	41·25	44 by 38·25	46 by 35·75		
9	135	43	46 by 39·50	48 by 37		

Thus a lens 35 by 26 mm. or one that is 37 by 24 mm. or one that is, say, 36 by 25 mm. would equally be a standard number 8 oval, their perimeters being the same, namely 97·5 mm.

The sizes Nos. 7, 8, and 9 oval are for globulars. Nos. 2, 4, and 6 round are respectively about equal in size to the $1\frac{1}{4}$, the $1\frac{3}{8}$ and the $1\frac{1}{2}$ inch round trial case lenses, the last being the size generally employed.

With a fair degree of approximation, No. 3 corresponds to the French 13 calibre, No. 4 to the $13\frac{1}{2}$, and so on; but the French calibres seem rather uncertain. Grooved lenses would be of the same perimeter, measured in the groove, as ordinary lenses are, measured around the knife edge.

It must be observed that although the figures do not correspond *exactly* to those of the American standards, yet each proposed British standard lens has the same circumference as some one of the former, so that they are interchangeable. It is impossible to vouch for the precise accuracy of the figures given, careful verification is needed. The calculations, however, have been confirmed by direct measurements taken from a set of wires, carefully prepared for the purpose of this paper by one of the wholesale firms.

Coloured Glasses.

The standardisation of colours is, it will be acknowledged, a subject beset with difficulties.

The standard that is suggested for smoked glasses is one which reduces, by one half, the intensity of transmitted light. Thus, if a candle is placed on one side of a grease spot photometer, and two similar candles at the same distance therefrom on the other side, the apparent intensity of the latter is reduced, by means of the standard smoked glass placed in front of them, so that it is equal to that of the single candle.

Or if a single candle is placed on one side of the photometer at a distance of 12 ins., and another covered by the standard smoked glass is placed on the other side at a distance of $8\frac{1}{2}$ ins., the intensity of the second shall then be equal to that of the first. The squares of 12 and $8\frac{1}{2}$ being respectively 144 and 72.

The proposed standard smoked glass from rough experiments made, seem to correspond approximately to the usual trade No. 1 smoked; but the tints at present used by different firms often present somewhat embarrassing differences. The experiments, however, ought not to be

made with the coloured light of candles, but with white solar light when determining the standard No. 1 smoked glass.

Standard No. 2 would be equal to two number ones placed together, No. 3 would be equal to three number ones placed together and so on up to some suitable dark shade, say No. 9. If lighter shades or intermediate shades were required, they would be numbered in half numbers, thus No. $\frac{1}{2}$ or $1\frac{1}{2}$. These proposed standards, of course, refer to plane glasses, which obviously must be accepted as our basis of reference, since they only are used in trial cases.

Attempts to devise a standard for blue glass have been in vain; photometric calculations here seem to be valueless, because the nature of the light is altered by the coloured glass, but no doubt, there are, among the members of this Society, some whose scientific knowledge of these matters will enable them to suggest a basis of standardisation.

Dr. Lindsay Johnson, some time ago, read a paper before the Royal Photographic Society on a system of colour standards in connection with colour photography; but they being based on spectrum hues would be, it would seem, of little value in connection with coloured glass.

The ordinary cobalt glass is by no means a pure blue; it transmits a very fair proportion of red rays. Most of you know the spectrum blue glass invented by Dr. Lindsay Johnson, in conjunction with Mr. Pillischer, of Bond Street, and you, therefore, also know that it differs very considerably from the blue glass commonly employed in the optical industry. Whether indeed cobalt blue should be used at all for optical purposes is an open question, but it cannot be argued here.

In THE OPTICIAN of September 5th, 1895, there is an article entitled "A scheme of colour standards" by J. H. Pillsbury. It treats of a method of systematising colour nomenclature and of forming a series of colour standards based on the hues of the solar spectrum and selected by a number of "colour experts."

These standards were to be adopted as the foundation of all colour work; and although the difficulties of producing pigments which represent the colours of the solar spectrum were very great, still they seem to have been, to some extent, overcome, and six spectrum colours, namely, red, orange, yellow, green, blue, and violet, were defined as standards. These standard pigments, also, do not seem helpful in producing a standard blue in glass to be used for optical purposes.

Naturally, green is not of any very great importance, since it is but

little employed; but if we did find a scientific basis for a standard in blue, a similar method would, no doubt, also serve for the green. Failing some scientific basis, it might be suggested that an arbitrary blue should be selected of a tint that might be said to correspond in depth to that of the No. 1 smoked, and this taken as No. 1 standard; then No. 2 would be equal to two number ones placed together, No. 3 to three number ones, and so on; the same as with the smoked.

There are many other things connected with the optical trade which could be standardised; doubtless, they will presently come to the front; for instance, no attempt has been made to deal with prism notation. This, as a subject of extreme complexity, may well be left for future consideration.

Instead of using the same numbers ranging from 1 to 9 or so for all optical standards, it would perhaps be as well to employ them only for the calibres of lenses and eye wires. For tints, the letters A to, say, H or J would serve, while for the spreads of bridges, we could have the numbers from 11 upwards or the letters from J onwards. Again, other series of numbers or figures could be adopted for standards in other matters. Or we could supply letters to qualify the numbers; thus S 1 to S 9 for smoked and B 1 to B 9 for blue glass, C 1 to C 9 for calibres, N 1 to N 9 for bridges, and so on. But these are merely matters of detail.

We must expect to be told that there is no necessity for optical standards; that no wholesale or retail Optician experiences difficulty in interpreting and filling each and every order or prescription received from customers. Be this as it may, in respect to any particular house, in its dealing with its customers, the argument can apply only to that house and not to the trade as a body.

From the position of the Worshipful Company of Spectacle Makers in regard to the trade, their co-operation must be obtained in fixing those standards that the Optical Society may consider necessary and suitable. The charter of the Guild enables it, to a certain extent, to govern and regulate the trade, and it is the prerogative and the duty of the Company to fix definitely all standards for the British Optical Industry. The Company has indeed made a start, since it has already fixed one standard, namely, that of knowledge of optics. As a matter of fact, there is no other body in this country, excepting the government that has sufficient influence or power to develop officially this important matter. The Guild is an independent authority and its decision would have the necessary weight with the trade. Already, as

you are all aware, some four hundred of the most advanced Opticians in the country are freemen of the Company.

I am sure that you will join with me in thanking those wholesale houses who so readily placed at my disposal various articles which assisted materially in the preparation of this paper, and I trust that the discussion which will follow will be beneficial to the wholesale, and retail optical industries of the country by helping to clear up any difficulties which surround the arrival at, and the adoption of, a complete system of optical standards.

LECTURE ON ABERRATIONS

By Professor Silvanus P. Thompson, B.A., D.Sc., F.R.S.,
Vice-President.

At a Meeting of the Optical Society on January 18th, 1900.

MR. PRESIDENT and gentlemen : When you did me the honour of asking me to give a lecture to the Optical Society, I happened to be in the position of having just given a half dozen lectures in this theatre to my Friday evening class, and it occurred to me that some one of the topics that I have taken in these lectures might be a suitable one for the Optical Society. I took advice on the subject and I was told that the lecture on Aberrations would probably be the one which appealed most to you, and therefore I propose to talk to you about aberrations.

My object is not to lay down the law for you, but rather to illustrate by experiment in such a manner as one can when one has a lecture theatre fitted up with special appliances,—and apparatus which has been used again and again for optical demonstrations—illustrating by experiment things which very often are not known from that source, but are only learned from books. Those who, whether they are connected with the optical trades or not, are obliged to read up the parts of optics that they do not naturally come across in everyday work, do not always have the opportunity to grasp fully that which the books describe, because they have never possibly seen the experiments shown. I think therefore that probably you will thank me if I make this lecture a series of experimental demonstrations, rather than if I were to put endless mathematics on the board in order to explain what already is explained in books. (Cheers).

In order further to save your time and mine, I drew up a table of what I call aberrations, or what I so term, at any rate, whether the books do or not ; and thanks to the kindness of the Editor and Publisher of The Optician I am able to give you this in printed form. You will observe that I have drawn up five classes of aberrations.

(See next page.)

TABLE OF ABERRATIONS IN LENSES.

CLASS I.	DUE TO THE MATERIAL.	MANIFESTATION.	REMEDY.
A	Chromatic Aberration... ... (a) of focal plane. (b) of magnification.	Colour tinging edges of images and of visible field.	Use Achromatic Lens made of two kinds of glass. Partial remedy, stop down with diaphragm.
B	Secondary Spectrum	Faint colour tinge in images of minute bright objects. Best seen by covering half the lens.	Use apochromatic lenses made of three kinds or glass, or special achromatics of glass chosen to annul secondary spectrum.
C	Streakiness	Streaks in glass. Images of bright points confused.	Reject. Glass is bad.
D	Double refraction	Doubling of image, or depolarising of light.	Reject. Cause, crystalline structure, or bad annealing.
CLASS II.	**DUE TO THE FORM.**		
E	Cylindricity	Vertical and horizontal lines not in focus at same time.	Reject. Lens has got astigmatism, being badly ground. but sometimes due to oblique mounting.
F	Spherical aberrations. (a) Central	Images of bright points blurred, even at centre of field.	Partial remedy, stop down. Curves badly calculated. Recalculate curves so that work of refracting shall be shared equally by various surfaces. Other remedy, use separated component lenses. In telescopes correct by retouching to eliminate error arising from surface being truly spherical.
	(b) "Coma"	Images of points not at centre of field blurred into pear-shape.	
	(c) "Radial astigmatism"	Images of points not at centre distorted into two focal lines at different distances from lens.	
G	Chromatic Differences of the spherical aberration ...	Faint colour-tinge of blurred image.	Remedy and correction as preceding.
H	Curvature of focal plane ...	Images at centre and at margin are in focus at different distances.	Different combinations of lenses needed.
I	Distortion of image in its plane	Barrel distortion or pincushion distortion of image.	Combination badly designed. Try shifting the stop.
CLASS III.	**DUE TO APERTURE.**		
K	Diffractional aberration ...	Spurious discs of stars. Sometimes faint systems of rings round star.	
CLASS IV.	**DUE TO MOUNTING.**		
L	Obliquity of mounting ...	Vertical and horizontal lines not in focus at same time.	Set straight in mounting.
M	Decentering	Image shifted out of direct line.	Lens badly cut or mounted. Thickest part must be in centre.
CLASS V.	**DUE TO REFLEXION.**		
N	Flare spot	Flare intruding across middle of field.	Combination not well adjusted. Try altering the distance between component lenses.

Perhaps we might dispose of the last one first, and have nothing more to say about it. The only aberration that we need trouble about due to reflexion is that commonly called "flare," which manifests itself mostly in a spot occurring right in the middle of the field. One comes across it in photographic lenses. It is much the best seen by getting a photographic lens that is bad in this respect. I cannot show it to you any better, so will not say anything more about it; but I think I shall say something about all the others, and try to show you some of them.

Now, going back to Class I., the aberrations due to material. Every material of which a lens is made operates on the waves of light; and whether it be a converging lens or a diverging lens, all that it can possibly do is to alter the shape of the wave-fronts of the waves that come into it. If the waves are coming from a practically infinite distance, every front marching along parallel lines, when they go through the lens they no longer come out with flat fronts. If they come out with a bulging front, then they will diverge. Every wave marches in a direction at right angles to its own front. (Illustrating.)

And now, if for any reason, the wave comes out with a bulging front, it will go on marching at right angles to its own front in this way, and therefore spread as from a centre. This is the reason why we have a divergence, produced by a negative lens.

Let us inquire a little further as to why and how that bulging is formed, how is it the middle part gains on the edge part?—Glass is a retarding medium, light will not go through glass so fast as through air, and therefore if you interpose a piece of glass thin in the middle and thick at the edges, the middle part of the wave only having to go through the smaller thickness of glass, is not so much retarded as the outer portions, and the result is that the middle part gains upon them, and the wave comes out bulging and diverging; and on the contray, if your lens is thick in the middle and thin at the edges, the light going through the middle has to go through a greater thickness, consequently now the middle part is retarded more than the marginal parts, and the wave-front comes out concave.

Now that would give us a real focus as everybody knows; but if the glass—and of course this is true for all glasses—does not retard all different colours of light equally, then the focus will not be the same for all different colours; there will be a shorter focal length for that sort of light which is most retarded, and a longer for that kind of light which is the least retarded. And so we have what is

called the aberration of colour, or chromatic aberration (No. A in the table); but, as a matter of fact, there are two different kinds which it is well to distinguish, which are very often not distinguished in books. A lens made of one piece of glass may produce a chromatic aberration in this sense, that it produces the image for different colours at different places. You have different foci when red or blue light is going through the lens. Here for instance (illustrating) it has its principal focus for red at a certain distance, and for yellow it has its principal focus at a little shorter distance from the lens; green light shorter, blue light still shorter and violet still shorter. You have different actual positions in space for the different foci of the different colours. That is what I have put down there under the sub-title (*a*). But you might have a lens with a different kind of chromatic aberration. You might have a lens such, that though all the focal planes were the same for the different colours, yet the images in that plane would be of different sizes. This arises from the circumstance that every thick lens has really more than one optical centre; you have, in fact, two so-called "equivalent points" which act as optical centres, and from which are measured the true focal lengths which determine the magnification. Now, it is conceivable that you might have an optical combination, bringing all different lights to a focus in the same focal plane, yet the widths of the images might be different. There always are, in fact, in a single lens two optical centres for red, as well as two for blue. Consequently you have a different magnification for a light of different colour. It is well to distinguish between these two sorts of chromatic aberration.

Everybody knows that you can correct in the main for chromatic aberration by combining together two lenses. You take a lens of crown and a correcting lens of flint; and that combination, if properly chosen, gives us an achromatic lens. But no achromatic lens can be achromatic for every colour of the spectrum; at the most it can only bring together two different colours—it may bring red and blue to focus exactly at the same place, but the yellow, green, orange and violet will not come exactly to the same place. This is because of what is called the irrationality of the dispersion. If you were to make a prism of any particular kind of glass and use that prism to produce a spectrum with the various lines of the spectrum spaced out as we know they are (illustrating), you would have a certain spacing out of those lines of the spectrum, the lines of different colours being differently spaced out. All kinds of glass crowd up the orange and

the red too much in proportion to their wave-length. If you produce a spectrum by means of a diffraction grating of fine lines ruled on glass, the spectrum is quite different, the spacing of the lines being absolutely proportional to the wave-lengths. Glass prisms always crowd up the red and orange relatively to the green, blue and violet. In fact, in the spectrum produced by a glass prism, the yellow, which should be in the middle, is always squeezed along toward the red end. But all glasses do not produce the same kind of crowding. Some glasses will produce more crowdings in the red piece of the spectrum, other glasses in yellow and green, and consequently you do not get an exactly proportional distribution of the different colours; and, therefore, because of the "irrationality" of the dispersion in different kinds of glass when used to bring together two particular kinds of light, there is always what we call a secondary spectrum. It is rather a stupid name: "residual spectrum" is better. You will see it in even the best achromatic lenses in the following way: Take your achromatic lens and use as the object a fine line of light; for instance, the line you might get by letting down the blinds and getting a slit against the sky. Another way is, of course, to make a slit in a piece of cardboard or a piece of paper and put a candle behind it. You get such a slit and a long way off you focus the image of that slit (illustrating). Now cover up half the lens with a piece of paper or anything else you like, taking care that the edge is vertical, if the bright line is vertical—if you are using a horizontal bright line, then you must cover up the bottom or the top half—and at once you will get a coloured tinge, red at one side and blue at the other. You can do it with any ordinary achromatic telescope objective. There are very good field glasses which illustrate this well. If you will focus a telescope on a bright line and cover up half the object glass, you will always be able to see this effect.

The eye is similarly shown to be not achromatic. Look at any bright light from a distance—say, a lamp—and then cover up half the pupil and you will at once perceive the colours of the spectrum, proving that the eye is not corrected for chromatic aberration.

Now, for the purpose of showing the achromatic aberration, I am proposing to use a very admirable lens which I bought second-hand in a marine store dealer's some years ago. I believe it was originally used for one of those small lighthouses on the quays at the port of Bristol—little lighthouses which they have, about 20 ft. high, to guide

the ships going round the corners of the harbour. It is an admirable lens, because it has every defect under the sun. (Laughter.)

Now we will have some light from an electric arc lamp thrown upon this lens, and we will endeavour to see whether it is achromatic. If it is, we shall have a white, bright spot as the image. But the spot, though bright, is not the only thing; there is a flare round it, the coma, due to spherical aberration as we shall see presently. We put a sheet of paper at the focus, and find the spot tinged with red, with rather a bluish centre; or, putting it nearer or further off, we get a very undefined kind of thing. Now if we cover up the middle of the lens, so as to allow the edges to produce their defects, we find that the chromatic aberration is a great deal worse; that the red margin is a great deal redder; but still better if we cut off from the light that we are using all the middle part of the spectrum, all the yellow and the green, and use only the colours at the extremes, we shall have red at one end, possibly with some orange, and shall have at the other end only blue and violet. To do that we might use violet glass, or purple, or what I am going to use in this little tank, Condy's fluid, that is to say, a solution of permanganate of soda or potash with water. This is the method I usually adopt, as by this means these achromatic aberrations can be shown exceedingly well. Look at the bluish centre (illustrating).

We may possibly show that again in another way. If you will look at this diagram you will see that the red makes a kind of an outer cone round all the other colours. Supposing we block out the middle of the lens, there is a cone of darkness, then a cone of light; and according to where we put our screen we shall get a red centre with blue outside, on a blue centre with red outside. Now if behind the lens we make a cloud of dust particles in the space to reflect the light we shall probably be able to see this without using any screen at all (illustrating). I have a tank full of smoke here, which may also be used to show this effect; you see a distinct cone of red rays outside the others. Let us try with another lens.

I may remark in passing, about that residual spectrum due to the irrational dispersion of glasses, that with the introduction of so many new kinds of glass it has been found possible to partly, though not absolutely, compensate for the irrationality of dispersion; for, although all glasses are irrational, you may be able to pick out pairs of glasses which are about equally irrational. For instance, if you found a glass which crowded up the orange part of the spectrum more than other parts—a crown glass which crowded

up the orange—you might also be able to find a flint glass which also crowded up the orange, and out of those two you could make a better achromatic lens than by taking that particular crown with a different flint. Indeed it is one of the chief advantages of the new glasses made in Jena—that you can correct more or less for all parts of a spectrum; you can get nearly all the colours right without any residual error. In Schott's catalogue you will find certain pairs recommended, because they are pairs that will work together in that way.

Here is a lens—a plano-convex single glass lens—and we will focus the beam nearly parallel on to it. If I cover up the greater part of the surface of the lens, so as only to show the marginal part, we shall exaggerate the aberration. Now if we cover it with purple glass we shall have this spot with a red margin round it (an orange-red margin with a purplish interior), or we shall have a purplish margin with an orange interior; a red margin with a blue interior, or a blue margin with a red interior. (Cheers.)

Now we must go on to the next point—aberrations C and D—C, want of precision of focus, which one finds if the glass is streaky, in which case you can do nothing with the lens; and, D, the aberration which arises if your material, instead of being singly refracting, is double refracting. A double refracting material is commonly either a crystalline body, or, if it is glass, it is badly annealed. I have some lenses here which are made of crystalline bodies. There is a quartz lens, and there is another. This one I owe to the kindness of Mr. Dixey, who was on the look out for a "good bad one" for me. This quartz lens is beautifully wrong, the crystalline axis is right across the middle. The crystal is exactly what it ought not to be—cut parallel to the axis (the axis is marked on it) with the consequence that it actually produces double images. You do not see that very well, because it has rather deep curves, unless you neutralise it. Neutralise one of these doubly refracting lenses with an ordinary positive or negative lens, and examine; and you will find, if you look through the edge at any bright body, any bright line, you get two images. This one actually does produce two images by double refraction.

Double refraction may often occur to such a small extent that you do not see it at all. Here is a lens that I use quite often for projecting objects on the screen, and it is very good so long as one is not working with polarized light. But when one is projecting on the screen with polarized light, I cannot use it in the usual place somewhere near the object, and between the polarizer and the analyser.

When there should be darkness there appears a faint whiteness right across the middle; in fact a white cross. One or other of the lenses in the combination is badly annealed: hence the combination depolarizes.

Now we come to the aberrations which are due to form—to the shape of the lens. We will suppose the material to be otherwise perfect, yet if the shape is imperfect for its purpose, then we shall not have accurate images formed. And the first error that I choose to name is the error of cylindricity—that is to say, the lens has been ground not spherical, as it ought to be, but with curvatures which are more or less cylindrical; we shall, of course, have aberrations, and the aberration above all others which is present here, if we employ a lens that is cylindrical, is, of course, astigmatism. We shall not have the vertical and horizontal lines of an object come to the same focus in the same plane.

It is very easy to illustrate that, provided you take an object that shall be composed of vertical and horizontal lines. I will take this lens, as it happens to be the most convenient for my purpose, and I will use it to make an image of this object. The lines are simply scratches ruled upon a sheet of smoked glass. Here, on the little screen, we will make an image of that object with vertical and horizontal lines in focus at the same time. Now we will take the cylindrical lens and put it with this, and it will give to it the same property as if this itself had cylindricity of curvature. We find we can focus the horizontal lines. Somewhere else we shall be able to focus the vertical lines, but we cannot get them both in focus (illustrating); and therefore we do not get a sharp focus at any place at all. That is clearly an astigmatic lens. It is afflicted with astigmatism in the proper sense of the word, as the eye might be afflicted.

I will show that again in another way. Using a little screen to catch the images, of course with the spherical lens alone, we get a cone of light which comes down to a point, if we have it properly centred; you can see the cone on my scattering dust in the air as before. Now, if we put the cylindrical lens along with it, so as to make the combination astigmatic, what shall we have? A cone which flattens to a line in one particular place and then widens out again to a small circle, and then flattens horizontally to a line at right angles to the former one. We have two focal lines and no focal point. That is what we may call pure astigmatism.

The effects of astigmatism of the eye are very well known, I have

no doubt, to you all, and I have been trying for some time to find whether I could get pictures which would show to an audience how a man who had an astigmatic eye would see something—what was the particular effect of the aberration of the eye which possesses astigmatism. I found the very thing I wanted issued by Messrs. Taylor, Taylor and Hobson, as an illustration of the good and bad behaviour of lenses. This first picture is to illustrate simply a set of circles, black and white, as seen by an ordinary eye, an eye in good condition, and then the next one is a thing as seen by an astigmatic eye, with vertical parts in good focus and horizontal parts blurred.

The camera lens is never astigmatic in this sense. Right across the whole field you never have this aberration. In this sense, no telescope, no opera glass, no camera, is astigmatic. What they call an astigmatism in a camera is something quite different.

The next aberration due to form is this: If the form of the lens, the form to which it has been ground, is truly and perfectly spherical, then, *because* it is truly and perfectly spherical, there will be aberrations. I know that some people have got a curious idea—I think it is the people who do not think for themselves, or who do not read accurately—that spherical aberration is an effect which lenses show when they are *not* truly spherical! It is just the other way about—it is because they are truly spherical.

Suppose light is coming out from a point, and you want to focus it at some other point, and you are taking a lens which is intended to do the work of collecting the rays which come out, the lens in between must turn the convex wave-front into a concave one. Now you want all the rays to be brought down to a focus at the other point. Clearly those rays which are very near to the axis have only to be turned through a small angle. Those rays which are out further have to be turned round more, and those rays still further, still more; the lens has to turn round these central rays a very little; those a little further out still more and so on.

If you take a double convex lens, which will show the spherical aberration you want to produce, having its curves perfect portions of spheres, the marginal parts will turn the light round too much, and bring it to a focus too soon—sooner than the central parts. That is to say these portions are too curved; they ought to slope back more. This same difficulty occurs with reflecting telescopes—with the concave mirror of the telescope—and they get over it in that case by grinding away the edges so that they shall not form a perfect sphere

and in refracting telescopes the object glasses are also corrected by retouching. They must make them too flat a curve to begin with, and gradually work them down, and not produce true sphericity; but this will not do for ordinary work, for small telescope lenses and opera glasses and spectacles; one cannot go fiddling with local retouching to alter the curves; you must make the best and the truest spherical surfaces you can, and therefore have got to "correct." Now what is the golden rule for spherical aberration? The golden rule for spherical aberration is very simple. It depends on what you want to correct. Suppose you are going to use a parallel beam, and you intend to bring it down to a focus. You should strive to arrange your lens so that the two surfaces, the surface where the light enters, and where it emerges, perform equal work. If you used a lens of this shape, for example (plano-convex) with the plane side towards the source, clearly the light would go in straight. The whole of the work of deflecting is given to the second surface. Turn the convex face round the other way; then you have some of the work of refracting done at the first surface and some at the second. That will give you a sharper image of the centre of the field for the case of parallel beams of light: but not perfect. For the most perfect simple lens in this sense, using crown glass, the ratio of the radii of curvature would be about 6 to 1, with flint 5 to 1, with diamond lenses 4 to 1. This is the particular case of *parallel* light to be brought to a focus at one point. For the case I gave you first—bringing light from a point on one side to a point equally distant on the other—the work of refracting must also be divided equally between the two surfaces. The best lens for *this* purpose, the lens freest from spherical aberration, is the equi-convex.

Now this kind of correction for the middle of the field, which is commonly called spherical aberration, and is the correction so described in the books, is only one of the spherical aberrations due to the form of the surface, and it is put down here under the head of "(*a*) central." Correct this as well as you can; you do not absolutely remove the spherical aberration even by proportioning the radii as 6 to 1. The best course you can adopt is to divide the work equally between the two surfaces. Suppose you get for parallel light the correct curvatures of the lens. But even then, though it may be spherically as correct as possible, if you use that lens for anything other than the purpose it was designed for, then it is no longer spherically correct. You can correct spherically for but two points only of the axis. In fact you might correct it for any two conjugate points.

Here is a drawing to illustrate how the different zones of a lens produce unequal effects, the marginal part turning the light round too much, making the focal length too short, and the middle parts making it too long. I wish to show you this. My big lens is admirable for the purpose of showing you how the rays are crossing one another (illustrating). I suppose it is pretty obvious that we have a kind of hollow curve all round here, an inverted arch. That in itself is evidence of spherical aberration.

Look at these rays where they cross the diameter; crossing and crossing and crossing they form a kind of arch, a "caustic-curve," as the result of the greater steepness of those from the margin as compared with these from the centre. Now—we will cover up this lens so as to allow light from only certain parts to come through, and we will take first of all light from the centre and near the centre only; then, if I scatter some chalk dust into the air, you will see the middle ray. Smoke will help us here. We are using the middle of the lens, and the region near the middle, and you see where these rays cross, marking the principal focus of the lens. Now I will open another pair of holes which are wider out, and from this wider zone of the lens the focus is nearer in. If we have the rays all going at once, you will see how the caustic curve is built up.

Now so far I have spoken only of this spherical aberration as affecting the question of whether you can get a sharply defined image at the middle of the field. For telescope work that is all you want. For you can always so turn your telescope that the star you want to look at comes to the middle of the field. But if you want to do anything more, if you want to look at sun spots on the disc of the sun you cannot have it all focused at once. As soon as you wish to measure the distance from star to star, at once you find that the correction which is suggested to give you no spherical aberration in the middle of the field leaves you with all sorts of aberrations everywhere else; in fact, when you have corrected the middle of the field for spherical aberration you have only got rid of the first term of the series of terms of which the aberrations consist.

The second term in the series of spherical aberrations is this,—that if you examine all the parts other than the centre of the field you discover that points which ought to focus sharply in the outlying regions do not focus sharply. Suppose you get the lens so arranged that for a point-object right on the axis you get a sharp point-image. Leaving the centre of the field you try it with some object which does

not lie on the axis, some object on one side, and try whether near in or far out you can get a sharp-image. You do not get it at any point. Instead of that you get things which are nearly oval in shape or like *this* or *that* (illustrated). These curious specks you get for the various images of the oblique projections of points, if the lens is not corrected, or only corrected for the middle of the field. This goes under the general name of "coma." I suppose it is meant that it looks like a comma in shape, or a comet.

I propose to show you this defect of coma. I have arranged here a little constellation of stars, made of small incandescent lamps, so that we may have not only one point but a number of points to be put into the field of view at the same time. Now this plano-convex lens, which is not at all a bad one for a single lens, does not profess to have the best shape for correcting spherical aberration, it is not achromatic, it has all the defects under the sun, except, that is as far as I am aware, there is no cylindricity about it. Let it be used to give us the images. We will try and get it placed opposite the middle of the constellation so that we may have one star at any rate central in our field of view.

Now you notice that every one of those stars, even the middle one, is fringed by a round patch. That is the coma (illustrating). We have no sharp focus anywhere except of the stars about the middle, which are fairly sharp, but not absolutely so. You might have a lens perfectly corrected for the centre, yet all the oblique images have the coma. On turning the bulging side towards us we have the coma outward instead of inward, and the definition in the middle is worse than before.

Some forty years ago a certain learned astronomer, Seidel, gave a very elaborate theory of the five different kinds of spherical aberration. So far as I know Seidel's theory has never been published in England. It is to our industrious, patient colleagues in Germany that we have had to look for the development of the theory of spherical aberration. It is true that Airy and Coddington and Herschel made many important discoveries, but the theory of getting a true image in a flat field we owe to Seidel.

He enumerates the aberrations in the following way: there is the general error of incorrect focusing, of which the first term, when corrected, gives you sharp images at the centre. This is what is ordinarily called *spherical aberration*. Then there are remains of the other errors, of which the next one to get rid of is *coma*, and after

that there remains an error which is called *radial astigmatism* which I will show you next. After you have got rid of radial astigmatism there remains an error called the *currature of the surface* of the image. The image is formed on a curved surface, instead of on a flat surface, so that it cannot be in focus all over the screen or plate at once. If you had a curved film for photographing upon you could avoid this defect. You could have a lens so designed that it would give you an absolutely sharp image all over a curved plate. And that leaves the fifth and final aberration—the *distortion of the image* in its own plane, the pincushion shape or barrel shape, as the case may be. These five aberrations cannot be corrected except by following out what is indicated by mathematical calculations as to the terms of the five errors that I have named. The corrections are these: first, for spherical aberration corrected as to the centre; second, the correction for coma; third, for radial astigmatism; fourth, the correction of the curvature of the image; and fifth, for distortion of the image in its own plane.

Now to correct five successive errors of this kind and to correct at the same time for two chromatic aberrations, and to give a lens a definite focal length means that you have got to fulfil eight conditions. You have five conditions imposed to get rid of the spherical aberrations; you have two conditions to fulfil to bring two colours together without achromatic aberration; and you have the eighth condition, namely, the prescribed focal length; that is to say, you cannot possibly produce a perfect lens unless you have eight variables in the lens itself.

If you are going to use two kinds of glasses, it gives you two variables. Then you may vary the different radii of the curvatures. If the lens is to be cemented, two of these radii are obliged to be the same, and you have, therefore, one variable the less. You cannot get rid of eight different conditions that are imposed upon you unless you have at least eight variable quantities. If you have three lenses, separate pieces of glass, you have there six surfaces, the curvature of any one of which you may alter; when you are designing the lens you have got two distances which you may alter, and you have the possibility of using three different kinds of glass. Or say two outside of the same kind, the middle one different, two kinds of glass, two distances, six surfaces. Ten variables, you see, and that is quite enough. Some designers attain the end by means of three or four lenses cemented together. Observe how it is attained in a photographic portrait lens. The whole system is composed of two members—a front lens and a back lens. Each of these is in turn composed of two

or more single lenses made of different kinds of glass, usually cemented together, though sometimes the individual members of the back-lens are separated by a layer of air. Further, each member of the combination is separately corrected for chromatic aberration; and they are so designed, of such thicknesses and at such a distance apart that the spherical and distortional aberrations of one member compensate as far as may be the aberrations of the other member. Lastly, the central "stop" assists in equalizing the aberrations at different parts of the field, and improves the marginal definition, though at the expense of the general brightness of the image.

This study of aberrations is necessary for this simple reason. You need only correct for the middle of the field in telescopes. In field glasses you have a rather wider angle. For opera glasses you want a very wide field, but people are not so particular here so long as they get the middle defined all right. But when you come to wide-angle photography, where you must have a wide angle with a large aperture to get the greatest amount of light, and where, particularly for process work, you must have no distortion and no error of focusing, and, in fact, perfect correction right up to the margin of the wide field, then this study of the five aberrations is essential. It becomes an absolute necessity: and the good lenses which are designed by modern makers are practically designed deliberately by knowing what are these five spherical and two achromatic conditions which have to be fulfilled, as well as giving the prescribed focal length; and the calculations are based upon these five equations of Seidel.

Now we have got here a lens which produces coma and it shows you how it is produced (illustrating). These different rays strike against the different parts of the lens, and instead of being brought to meet *there* where they ought to meet seem to have met across over there in space. It is the caustic-curve of the long tails of the coma displayed out as you see. The width between the outside piece and the next zone of it, *there*, arises from the width between the rays from the outermost part and the next outermost part of the lens. It is this outer zone of the lens that is responsible for that streak (illustrating).

If you could, from this oblique pencil, cut out only these rays which are contributions to the central part, you would of course at once reduce the tail of the coma and get a much sharper image. The object of the stop is to prevent the oblique pencils going through the middle of the lens and to make them go through the other part of the lens. That is exactly the way they do, if you notice, in landscape lenses.

The stop put in front lessens the coma. To cure the coma fully, you have to make sure that all zones of the lens have equal focal lengths. Then, following an earlier calculation of Petzval's, Seidel showed that to correct the radial astigmatism you have got to fulfil a very precise condition between the radii and the indices of refraction of the lenses that are used in combinations.

Suppose central aberration, coma, and radial astigmatism all to have been eliminated, then that leaves two of the five aberrations—the curvature of the image and the distortion in the plane. The curvature of the image can be corrected in compound lenses by a very simple process, namely, by slightly separating the front and the back components from one another. The diagrams on the wall are intended to illustrate this.

The only remaining kind of defect is, then, distortion of the images. This can be got rid of by proper disposition so that there shall be no more magnification at the margin than there is at the centre.

I have here just a simple old-fashioned lantern microscope, and if I put a good lens on—not a very powerful one—we shall get, of course, a very fair image on the screen. Now, I change that good lens for one that I know to be a bad one, and at once you see we have a distortion. The images of straight lines are no longer straight.

With regard to spherical aberrations a great discovery was made a few years ago; and again, I have to say, made in Germany. They found that they could produce a crown glass, for instance, *this* one, with a remarkably high refractive index, 1·61. The distinction is not nowadays so much "low" and "high" index; it is whether the glass has great dispersion relatively to its refraction or not.

We have, nowadays, crown glasses that have actually a higher refractive index than some of the light flints, while at the same time having a lesser chromatic dispersion. This new Jena glass is simply invaluable in permitting of achromatic combinations which give a far flatter field than was previously possible with the old kinds of glass.

There remains but one matter to be considered, viz., the aberration due to aperture, sometimes called the aberration of diffraction, a thing which is an immediate consequence of the wave nature of light. If you have a lens collecting the waves over a considerable area with a wide aperture, and the wave comes out, as I explained at the begining, concave, so as to meet at a point, you do not, even when every correction has been made, and everything is as perfect as possible from the optical point of view, have, and you never will have, an absolutely

sharp *point* there as the image of a distant bright point. And for this simple reason, that the waves from the different parts of the wave-front will *interfere* with one another.

Diffraction effects on a certain scale depend upon what is the size of the waves you are working with, also upon the length of the focus, and upon the amount of the visible aperture. The wider the aperture, up to a certain point, the less you will have of this trouble; the smaller the aperture, again up to a certain point, the less you will have. Anything very small or very large is distinctly bad. You are never troubled with it, however, except when you are dealing with long telescopes, and very accurate definitions of small stars. Then you get small bright discs, with rings of light round them, instead of small bright points. I would have liked to show you this experimentally; but it is an effect which cannot well be projected upon the screen. So I must content myself with pictures of the effect.

I have two or three photographed figures here showing the kinds of aberration which you get due to diffraction, due to the interference of the waves. You see a little round disc of a definite size, say about 1/100th of an inch, and then rings of coloured light round it, gradually getting greater and greater. It is an aberration which mars the finest work. You cannot get rid of the fact that light waves have a definite length. Light waves interfere, and diffraction will be set up. Diffraction is not simply, as many people are in the habit of supposing, caused by light grazing against the edge of an aperture. Diffraction occurs wherever you have waves. When you have a large object you do not notice this at all. When you want to get accurate definition of these small objects, then this comes into play. The best account of it is in the article on "Optics" in the Encyclopædia Britannica, written by Lord Rayleigh, who is one of our greatest authorities on diffraction and diffraction effects.

I am very sorry that I have kept you so long on this. I am exceedingly sorry I have not been able to show you this last thing as well as I would like to have done, but I must ask you to kindly forgive me in that respect, and to be willing for once to take the will for the deed. (Loud cheers.)

PRESIDENTIAL ADDRESS

By Dr. R. Mullineux Walmsley, F.R.S.E., &c. (*President, 1900*).

Delivered at a Meeting of The Optical Society, on March 22nd, 1900.

IN taking the Presidential Chair at the first meeting of the Society at which I have the honour to preside, it falls to my lot to deliver the presidential address which is usually expected from the occupant of the Chair on such an occasion. Whether such addresses in these latter days fulfil any useful purpose or not I scarcely care to enquire, but there are certainly indications that they have, to a great extent, outlived the objects which led to their foundation. I shall, however, leave to my successors the task of examining and deciding whether the time given to a presidential address would not be more profitably occupied with a paper upon which a useful discussion might be founded.

The discharge of the duty makes me feel peculiarly the difficulty under which I labour in following such an able chairman as Mr. Thornthwaite, and I would like to preface my remarks with a very sincere acknowledgment of the high value to the Society of Mr. Thornthwaite's labours during his tenure of office. In the first starting of such a society numerous difficulties have to be faced, which, though often not important in themselves, may very seriously retard an early development if not properly treated. My hearers will, I am sure, agree with me when I say that Mr. Thornthwaite has met all these difficulties in a manner highly conducive to the welfare and progress of the Society, and has left to his successor few, if any, of such special initial difficulties to be dealt with; in fact, at the moment it is not easy to recall any which specially come under this classification. The guidance of our past president has been so politic and business-like that we may now regard ourselves as fairly launched upon a career which it lies in our own hands to make useful and distinguished.

Notwithstanding the fact that the Society has been successfully launched it is still a young Society, and I feel very deeply the responsibility of being placed at the head of its councils in the second year of its existence. That year, and almost certainly several of those which follow, will necessarily be years of development and of growth,

and questions are bound to arise from time to time which will require very careful handling. One such question is even now pending, to which I shall not further allude than to remind members that matters which have recently been the subject of lively discussion are not yet settled.

At the outset, however, I may mention that it has recently come to my knowledge that we are regarded by some of the members connected with the optical trade as a Spectacle Makers' Society only. This is a great mistake, and I cannot too strongly emphasise the fact that the Optical Society is intended to include *all* who are interested in the science of optics, whatever the particular branch may be to which they devote their chief attention. I would specially mention the photographic trade, for I believe it is with this section that the misconception referred to above has most largely arisen. I sincerely hope that this hint will be sufficient and that the members of the photographic section of optical work will join us in large numbers in the early future.

There are several questions which it appears to me the Society may well take up during the coming year with great advantage to the important department of practical and scientific work which it represents: I shall, however, only allude to three:—

One of the objects formally set down as being amongst those for which the Society is established is "to promote the establishment, adoption, and recognition of standard sizes, gauges, calibres, templets, and methods for universal use in the optical trade." This object is certainly a large and comprehensive one, nor can it be expected that it will be successfully carried through in a single year. There will be much work involving the consideration of minute details in many directions, work which will tax the technical ability of our best experts, both in the optical trade and in the domain of pure and applied science, but the advantages to be secured are so evident and so important that the initial stages of this work should be faced without delay. Work of a similar kind has been undertaken by other societies in the past, and successfully carried through. I need only allude to one instance, with which perhaps I am more familiar than any other, viz., the work done by the Electrical Standards Committee of the British Association. I would remind you that this Association is a private Association like our own, but some 40 years ago, when Electrical Standards were in a most chaotic condition, it appointed a committee, consisting of men well qualified for the work, with the main object of

evolving order out of chaos. Year after year this committee carried on, patiently but thoroughly, the work entrusted to it, making reports from time to time. The rate of progress varied, but there always was progress, and eventually the work became of international importance and was officially recognised. We may venture, I think, to hope that, in a less extensive sphere, this example may be successfully followed, and a proportionately valuable work accomplished in the end. I would therefore suggest that the Council should formulate at an early date for the consideration of the Society, some practical proposals in the direction of carrying out this, not the least important of the objects for which the Society has been established.

Another matter which appears to me ripe for full discussion and consideration is the question of the affiliation of local Provincial Societies with the Optical Society of London. It may be said that we are rather young to be seeking to extend our borders in this direction, but these are days when events move rapidly. They are also days in which the workers in any one line of progress are scattered all over the country, and in which the facilities for bringing to the notice of those interested the results of such labours should be made as great as possible. Even the older societies are feeling the necessity for co-ordinating the whole of the work of the country in their particular lines of thought. Within the last two years the Institution of Electrical Engineers has amended its rules to allow and to encourage the affiliation of local Societies with the Society in London. Besides acting in the direction indicated, affiliation will probably lead to the holding of some of the meetings of the London Society at the headquarters of one or other of the Provincial Societies, and thus encourage that scientific and social intercourse of men with similar aims, which is one of the first objects of the Optical Society.

A third question, which I hope the Council will consider in the near future, is the desirability of organising on an important scale an exhibition of optical and photographic inventions and manufactures, which should be thrown open to the public at large. The Royal Photographic Society has for some years past held an exhibition, including not only photographic apparatus but also apparatus of various kinds. Considering the wide scope of the optical and photographic industries, might not we very well organise a public exhibition on similar lines?

My reason for putting forward this idea at once, is that the Paris Exhibition will no doubt be the occasion of bringing together an immense concourse of strangers from all parts of the globe. Naturally,

many of these will visit London, and so the British firms who, for one reason or another, will not show in Paris, might well be afforded an opportunity of exhibiting under the auspices of the Optical Society. If the Exhibition were a success, which I do not doubt, it might be made an annual affair. I think the Optical Society need not take any risk in the matter. It will be easy to get out an estimate of cost; and the revenue from the letting of stands, and other sources, would undoubtedly cover the outlay whatever it might be, without allowing for admission money from the public. This latter item would afford a margin for all contingencies.

It is usual to include in an address of this nature some reference to topics connected with the science or the applications of the science from which the Society takes its title, such topics as a rule being of particular interest at the moment at which the address is delivered. In looking round for subjects of this kind one cannot but be struck with the very wide extent and importance of the science of optics and its applications, a feeling which was emphasised by our past President in his address delivered in October last. As a matter of fact, there is scarcely any limit to the interesting topics which might be dealt with, and I should far exceed the time I may assume to be at my disposal if I attempted anything like a comprehensive survey. I have, therefore, decided to confine my special remarks of this nature to two sections of the subject, which appear to me to demand special notice just now.

At the present moment the minds of all Englishmen are turned in one direction, viz., towards the events which are happening in South Africa and which are fraught with such wide importance to the English speaking races. The subject of "Optics and the War" is therefore one which cannot fail to be interesting, and I shall crave your indulgence whilst I make a few very cursory remarks upon the appliances, etc., which our science has either directly or indirectly supplied to the equipment of a modern army in the field.

The present war has in many respects been a revelation to military men, and in none perhaps more so than in the great increase of the distance at which the opposing troops come into actual conflict. With the modern rifle and the modern field gun, not to mention the guns of position which have been so freely used in Natal, it is scarcely an exaggeration to say that the conflict begins before the opposing armies can clearly see one another. It is therefore of very much greater importance now than it has ever been before, that optical appliances should be largely supplied as mere aids to vision, for use during an

action, as well as for scouting purposes. One of the directions, not the least important, in which our War Office was found unprepared was in the supply of field glasses for the use of the army in the field. I do not propose to weary you by entering in any detail into the questions underlying the production of a good field glass, suffice it to say that they are thoroughly well understood. I may, however, be permitted to make a remark in passing upon the beautiful prismatic glasses recently introduced, where the great advantage of compactness and high optical power have been secured to an extent not hitherto possible. In addition, this particular form of construction renders easy the adjustment of the pupillary distance accurately, and thus enables the user of the glass to shut out completely all extraneous light and secure the highest optical advantages which the glass offers.

This question of the use of field glasses for ascertaining the position occupied by the enemy is complicated by the modern developments in the production of smokeless powders, so much so that in some of the letters written home men have said that they were falling with bullets from an invisible foe, it being impossible to detect where the shots were being fired from. How best to meet this difficulty requires careful experiment, which I would suggest some member or members of this Society might carry out on the rifle ranges of the country during the coming summer. Suggestions have been made for combining cobalt or other blue coloured glasses with the field glasses, or in the shape of spectacles, the idea being that the purple flame of potassium might be more readily detected when viewed through such coloured screens. Doubt has been thrown upon the efficacy of the device, and it is eminently one therefore to be brought to the test of experiment. As the lives of men are dependent upon the successful solution of these optical questions they should not be allowed to rest.

Perhaps the most fascinating direction of the application of optics to war is in the production of range-finders. This subject has attracted attention from the earliest times in which projectiles were capable of being thrown with approximate accuracy to a fair distance. Nature' range-finder is found in the binocular vision with which we are endowed, the pupillary distance being the base, and the muscular accommodation the means by which the range is unconsciously estimated. For short distances by long practice we have more or less acquired an accurate perception of range, hence it is that in shooting game in the field the practised shot will estimate both direction and

range automatically. For the longer distances employed in war, this Nature's range-finder breaks down, more especially as the opportunities for training it are not sufficiently numerous, and also because for long distances varying atmospheric conditions so enormously alter the visual effect produced on the retina. Optical range-finders are therefore a necessity in modern warfare, and hundreds of inventors have applied their talents to the solution of the problem.

The chief conditions to be fulfilled are easily stated, but unfortunately are not so easily fulfilled in practice. They may be summed up as follows:—

1. The range should be rapidly ascertainable and preferably by not more than one observer.
2. The range should be indicated directly on the instrument without calculation.
3. The percentage margin of error for long ranges should be small.
4. The method of using the instrument should be simple.
5. The instrument should be capable of standing rough usage in the field.

One of the simplest methods is to estimate the distance by the size of the image produced in the field of a telescope by some well-known object, such as a man or a horseman seen at the distant position This is the principle of the Elcho range-finder, in which a marked diagram is introduced into the eyepiece of a telescope, the image of an infantry man or a mounted cavalry man being viewed against the diagram in which certain marks allow an estimate of the distance to be made. More recently a method has been devised for estimating the distance by attempting to obtain a stereoscopic effect for marks placed in the field of a binocular. Both methods strike one as scientifically crude. In the first it is necessary to assume that all men and all horses are of the same height. It also requires that the enemy should expose himself clearly, which is not the Boer method of fighting.

More scientific range-finders may be divided into two classes, first, those which determine the angle subtended at the distant object, by a base of known length at the position of the observer, and secondly, those which depend upon the measurement of the length of the base subtended by a given angle. The first class is by far the more numerous, and may be further sub-divided into those instruments in which only a short base is used and the whole work done by a single

observer, and those in which a much longer base is employed usually, though not necessarily, necessitating the joint observations of two or more observers. Time would fail me to even enumerate the numerous instruments that have been brought out in these classes, but a reference to a few of the best known may be of interest. One of the simplest consists of a box sextant, in using which the direction at right angles to the direction of the distant object is first laid out, and then by walking a measured distance in this direction and taking a further angular observation the data for solving the right angle triangle so observed are ascertained. A simple calculation will give the range. In the field, however, one does not want to be troubled with calculations; the instrument should read off at once on a scale the actual range sought.

Most of the range-finders using a long base employ either the sextant principle, or in the simplest forms total reflecting prisms of known angle. For instance, the "Weldon" contains three prisms, one for giving the right angle, another with an angle of 88° 51′ 15″ which gives a base of $\frac{1}{30}$ of the range, and another of 75° 57′ 50″ in which the base is $\frac{1}{4}$ of the range. This method does not admit of high accuracy.

The Labbez telemeter is practically a box sextant and is to be used with a base of 30 units. With the instrument set at zero the mirrors are inclined at an angle of 45°, thus giving a right angle between a "mark" and the "object." The observer has then to advance 30 units towards the mark and alter the index mirror with a micrometer screw until another sight of object and mark is obtained, when the scale reading will give the range in terms of the unit used. An improvement suggested by Steward consists in retiring from the mark, in line with the right angle point; this is much more convenient and only involves observing an acute instead of an obtuse angle.

The Dredge Steward Omni-telemeter, a highly finished instrument, contains further improvements in details, and especially an adjustment to meet the not infrequent case when a "mark" exactly at right angles to the direction of the "object" is not quickly available. With a second observer using an optical square and a base line stretched between the two observers, any of these instruments can be used to obtain the range of a moving object at a particular instant.

The Watkin range-finder, which is very widely used, is also based on the sextant principle. The base is marked out by pickets and forms one side of the right angled triangle of which the range is another side

containing the right angle; the rectangular direction is ascertained by the use of the instrument. This base may be any convenient length, its actual size being ascertained by a further observation with the instrument upon a sub-base at right angles to the first base, and not more than six yards long. The length of the base having been thus ascertained, the movement of the index mirror of the sextant is controlled by an adjustment depending on the length of the base. An observation is then taken in the ordinary manner, the distant point and the picket at the right angle being brought into coincidence on the field (or horizon) mirror and glass by moving the lever controlling the index mirror with a micrometer screw. When coincidence is obtained the range can be read off on a spiral scale engraved on a drum which forms the micrometer head.

A range-finder based upon the use of a long base requiring two observers, but employing an electrical principle for the actual indications, was introduced by Lieut. Fiske of the United States Navy. At the two ends of the base which may be in the fore and after parts of a ship respectively, two pivotted telescopes are mounted; these are to be trained by two observers simultaneously upon the distant object, the observers communicating with one another by telephones fixed to their ears and in front of their mouths, leaving their hands quite free. When the distant object has been brought into the centre of the field of view in both telescopes simultaneously, the range can be read off upon a galvanometer scale. The galvanometer is placed in any convenient part of the ship, not necessarily at either of the ends of the base. The principle used is that of the Wheatstone Bridge, so well known in electrical testing. Each telescope carries a metallic wiper which moves over a resistance wire and alters the resistance of the different arms of the bridge. When the telescopes are parallel and therefore sighted for an object at an infinite distance, the bridge is in balance, and there is no current through the galvanometer. As they move from parallelism balance is destroyed, current passes through the galvanometer, and the needle is deflected. The scale is of course marked in yards or feet instead of in degrees. High accuracy is claimed for this instrument, but there are certain difficulties in the way of obtaining it. One great advantage is that the battery and the galvanometer with its scale can be placed in a position of safety where they cannot be reached by the enemy's fire. The telescopes of course are exposed.

Another principle used in range-finders is that of observing the

angle of depression from a position at a known vertical height above the object whose distance is required. To understand this principle it is only necessary to imagine an ordinary surveying level so mounted that the telescope can be depressed through a measured angle from the position of dead level. Placed in a position of known height the telescope is turned in the direction of the object, and is depressed until the latter is seen in the centre of the field. The angle of depression combined with the vertical height enables the distance to be calculated, but for convenience of use the depression may be made by means of a vertical micrometer screw on the scale of which the range can be read off instead of the angular depression. Without, however, some adjustment for different heights, the scale of the micrometer would only be available for one particular vertical height. An adjustment is readily obtained by using a double lever with a slider on one of the arms, by moving which over to a mark corresponding with the particular height, the scale on the micrometer can be made available for a variety of heights.

In the Brotherhood depression range-finder, made by Stanley, the observing telescope is fixed at the end of a horizontal arm, at the other end of which a longitudinal slot is mounted vertically. A tangent scale of distances corresponding to a particular vertical height is engraved on the side of the slot, and the infinity mark on the scale appears in the centre of the field of the telescope when the latter is dead level. The arm being trained in azimuth on the object the telescope is depressed till the object is sighted. The distance is then read off in the field of a small telescope mounted alongside the observing telescope, to the axis of which its axis is parallel. With one eye at the observing telescope, and the other at the reading telescope, a moving object out at sea can be readily followed, and its distance given from instant to instant. In this instrument a change of height would necessitate a change of scale on the slot.

The great disadvantage of all depression range-finders is that they require the vertical height to be independently ascertained. Their greatest use is probably in fortifications on the sea coast.

The range-finders so far referred to all make use of a long base. At the risk of wearying you I shall now say a few words about those which employ only a short base a few feet in length.

The most usual method adopted in this class of range-finders is to fix two 45° mirrors or total reflecting prisms at the ends of a base from 3 to 5 ft. in length, the light coming from the distant objects is

reflected towards the centre of the base, and deflected again at right angles, the two images being finally viewed in the field of a single suitable eye piece.

Adie used positive lenses in front of 45° prisms at the end of the base, and to bring the two images into coincidence one of the prisms could be rotated by a micrometer working at the end of a lever, the amount of rotation necessary depending upon the inclination of the two beams of light from the distant object. This inclination in connection with the length of the base gives the range, and as the base is of known length, the result can be marked off on the micrometer scale.

In this form, however, the instrument was not very accurate, but it was improved by the present Astronomer Royal in 1886. He used the 45° mirrors, because of certain difficulties in fixing the total reflection prisms. The objectives were also moved to the eye piece side of the mirrors, and coincidence was obtained by displacing one of the objectives transversely, the amount of displacement being taken as a measure of the divergence of the beams received on the two mirrors. Here again high accuracy, especially for long ranges, is not easily obtainable.

The instrument was still further improved by Professors Barr and Stroud, to whose paper I am indebted for some of these particulars. Keeping to the Astronomer Royal's arrangement of end mirrors and objectives, both the latter were fixed and coincidence obtained by placing in the path of one of the beams a small angle achromatic prism. It will be easily understood that by moving this prism nearer or further from one of the objectives, it is possible to correct the divergence of the beams and secure coincidence of the images. The amount of movement of the prism required for this purpose would be a practical measure of the divergence, and therefore of the distance of the object. An appropriate scale directly connected to the prism and moving with it enables the range to be read off against a fiducial mark. Several ingenious precautions are taken to neutralise changes of temperature and strains from ordinary handling, and with a 4½ foot base a 1 per cent. accuracy for a 3,000 yds. range is claimed to have been attained.

I regret that want of time will not allow me to describe a beautiful arrangement of prisms at the observing centre of this range-finder, by which the images received from the two ends are seen in the two different halves of the field of view, and coincidence obtained without any ambiguity caused by over-lapping. A further optical device

of a cylindric lens enables the position of distant lights to be found at night time.

This interesting division of the subject has occupied me so long that I must pass over with a mere reference some other optical devices used in warfare. Mention must be made of the ordinary sights on rifles and guns which are distinctly optical devices, many of them of great ingenuity. The orthoptic method of altering the aperture through which the marksman looks can also only be named. In addition, we have the telescopic sights so necessary especially for naval guns which have to be used upon a moving platform. Indeed, the problem of accurate firing from such a platform without such sights would appear to be absolutely impossible of solution. Mention should also be made of that useful instrument, the prismatic compass, many ingenious modifications of which have been devised.

I must now leave this subject as I wish to conclude my address with a few remarks on the "Border Land of Optics," a subject which is as far removed as it is possible to imagine from that of which I have just been treating.

The wide extent of the science of optics becomes apparent when we examine the points at which it overlaps other sciences. I may be accused of exaggeration, but I have solid ground for the assertion that the whole modern science of electricity and magnetism might be claimed as a branch of optics. I know that the statement is sometimes put in the converse direction, and that optics is claimed as a branch of the science of electricity. We need not dispute about this point, the interesting part of both subjects for my present purpose is that in which they distinctly overlap.

Faraday, who was one of the first to clearly see that there might be some connecting links, also discovered the first experimental fact connecting the two sciences in his classical research upon the rotation of the plane of polarisation of a beam of polarised light by the action of a magnetic field.

As long ago as 1856, Clark Maxwell published his electric-magnetic theory of light, in which he showed that the disturbance which transmits light may be regarded as an electric and a magnetic displacement in the wave front at right angles to one another, and also at right angles to the direction of the propagation. Electro-magnetic radiations, he asserted, would be experimentally discovered in course of time, and if when so discovered they were found to travel with the speed of light, the necessary quantitative evidence of the probable truth of his theory

would be supplied. In the years that followed, certain electrical measurements and comparisons showed that there was a velocity entering into many of the equations used by electricians, and that when this velocity was experimentally determined it was, within the limits of experimental error, the same as the velocity of light, viz., some 30,000,000,000 cms. or say 186,000 miles per second. The measurements were indirect ones, and it was reserved for Hertz, whose early loss we all deplore, to prove experimentally in 1888 the existence of the electro-magnetic waves, and to measure their velocity directly. For setting up the waves he employed definite electric oscillators capable of giving rapid discharges or disturbances, and for detecting their presence at a distance he employed electric resonators tuned to respond to particular rates of vibration. The waves were found to have all the properties of light waves, they could be reflected, refracted, polarised, diffracted, etc., the only difference was a quantitative one, viz., that the wave length was much greater than that of the ordinary light waves. I would remind you that the wave length within the limits of the visible spectrum extends from about ·00004 to ·00008 cm., and thus covers about a single octave of vibrations. Beyond the violet and the red, however, similar disturbances can be detected, though they do not affect the retina. The longest wave measured in these ultra spectral regions has a wave length of about ·0025 cm. The Hertzian waves have been found to have wave lengths varying from something less than a centimetre to many thousands of miles. The gap to be bridged for complete continuity is, therefore, not a very great one. Moreover, calculation shows that the ordinary light and radiant heat waves can be accounted for by assuming the dimensions of the oscillators which create the disturbances to be of atomic proportions We thus get an interesting glimpse into Nature's light manufactory.

Another peculiarity of the waves seemed to surprise people at first, viz., that many substances opaque to light waves are transparent to these electric waves, for instance, pitch, ebonite, paraffin wax, sulphur. brick and stone walls, and many other opaque bodies are transparent to the Maxwellian radiations. A little consideration, however, will show that there is not anything necessarily strange in this. A piece of pitch is no more solid than a piece of glass, and all that the difference in transparency for the various wave lengths shows is that the gross matter is selective in this respect. We know that it is partially so within the limits of the visual spectrum, and that within these limits some waves are transmitted more readily through certain sub-

stances than other waves. I need only mention without comment the case of coloured media.

One of the consequences of the electro-magnetic theory of light is that the refractive index of transparent bodies should be equal to the square root of their electric specific-inductive capacity. Measurement of the refractive indices and of the specific inductive capacities of many bodies have shown reasonable agreement with this law, and it is possible that the outstanding differences can be accounted for by considerations of wave-length for which we have not the experimental data to make full allowance. Another deduction from the theory is that the conductors of electricity should be opaque to the waves; a result which experiment also has confirmed.

Intimately associated with these waves is a subject which has bulked very largely in the popular journals of the day. I refer to wireless telegraphy, in which the waves I have been talking about are employed for the purpose of conveying messages to a distance without any intervening conducting wire, and even through stone walls and other artificial and natural obstacles. The Hertz resonators are not suitable as receivers for this purpose, and another receiving device has fortunately come to the rescue. Branly discovered that loose metallic powders which are almost non-conducting for the electrical current in their ordinary state become conductors when electro-magnetic waves fall upon them. Further, that they regain their high resistance when agitated, and so become ready to be acted upon again by a new set of waves. Marconi, who has worked most industriously at the necessary practical details, has succeeded in transmitting messages over 70 or 80 miles, and even farther. The tube containing the loose metallic powder is called a coherer, and is placed in an electric circuit with a relay. When the waves fall on the coherer a current passes sufficient to work the relay, thus closing another circuit which works the receiving instrument. Sensitiveness is restored by the coherer tube receiving a slight blow from the armature of an electric-magnet in the working circuit. Time will not permit me to go further into details, either of methods or results.

The production of light by electrical discharges is another direction in which the sciences overlap. The electric spark was one of the earliest phenomena observed in this direction. About the middle of this century the production of light in vacuum tubes by Geissler and those who followed him was a still further development, and as the vacua were pressed higher and higher the discharges became more and

more interesting. Eventually the kathode rays with their unforeseen properties were discovered and subjected to investigation. It will be within the knowledge of all my hearers that these rays proceed from the kathode or negative pole of a vacuum tube in straight lines and cause phosphorescence of the glass against which they strike; also that they can be deflected by a magnet, and by such deflection can be spread out in a form not dissimilar to a spectrum. They apparently possess the property of passing through aluminium, but recent research has thrown doubt upon this, the alternative explanation being that what is projected from the outside of the aluminium is not the same entity that strikes against the inside, though it has the same properties.

Investigations on the kathode rays led to the discovery by Röntgen of the so-called *X*-rays, the exact constitution of which is still a matter awaiting crucial experiment. If the rays are of the same nature as the light waves they are certainly of extremely minute wave-length even when compared with the minutest light waves that have been measured. One explanation of their peculiar properties put forward is that instead of being a series of numerous waves as in ordinary light, they consist of distinct and isolated waves following one another at relatively long intervals. In connection with them and the kathode rays, combined with the facts of electrolysis, interesting experiments and deductions made by Professor J. J. Thomson and published towards the close of last year, have tended to throw a doubt upon the atomic theory, which has been hitherto regarded as one of the safest deductions of modern science. Thomson's deductions tend to show that there exist bodies very much smaller than atoms, and to these he has given the name of 'corpuscles,' an interesting name for Opticians as we are all familiar with the celebrated Newtonian corpuscular theory of light. Thomson's corpuscles, however, are certainly not light corpuscles, in the Newtonian sense, though they are probably intimately associated with optical phenomena. They are estimated to have a mass a little greater than the thousandth part of that of the mass of the hydrogen atom, which is the lightest of the chemical atoms, and if their existence can be fully proved, the assertion of the chemist that the atom is a portion of matter which cannot be further divided, will have to be modified.

We have not yet exhausted the points of contact between optics and electricity. Kerr many years ago showed that if a beam of plane polarised light is reflected from the polished pole of a magnet, the plane of polarisation is rotated. Still more recently (1897) Zeeman

has pointed out that in a magnetic field many of the bands seen in the ordinary solar and other spectra become divided. If the light is travelling perpendicular to the lines of force of the field, the lines D_1 and D_2 can be split into four or six lines each, and these on examination are found to be plane polarised. If the light be travelling parallel to the magnetic lines of the field then the bands are usually split into triplets, the outer lines on either side being circularly polarised in opposite directions, and the central band plane polarised. The most probable explanation of these phenomena, and one which fits the experimental facts very well, is that in the phenomena of light we have moving electrical charges, carried probably by the corpuscles already referred to, the charges being acted upon in the magnetic field according to the well ascertained laws of electro-magnetic action.

Dr. Preston, of Dublin, whose early loss we have been called upon during the last few days to deplore, has shown that groups of lines in the spectra of different metals are similarly acted upon by the magnetic field, thus leading by strict measurement to the highly interesting deduction that the same kind of corpuscle enters into the constitution of atoms of different elements, and that probably the difference in the property of the elements is due to the different ways in which these more elementary corpuscles enter into the complex body that we have been accustomed to regard as the atom.

In the domain of chemistry we find a Border Land between it and optics in the now widespread science of photography. As you all are aware in this science, the light waves are used to initiate and to carry through chemical actions. The details are so familiar to all of you that I merely mention the subject in passing as a further instance of the overlapping of our science with another important branch of scientific thought and investigation.

Turning to the science of acoustics we find in the photophone an instrument in which the three sciences of optics, acoustics, and electricity have a common meeting ground. A beam of light which is exposed or eclipsed according to some pre-arranged method, falls upon the sensitive part of the photophone, alters the electrical resistance, and so can be made to produce ultimately a telephonic effect. Again time does not allow me to elaborate the details.

One other instance and I shall not trespass upon your patience longer. The whole science of radiant heat is a branch of optics. In it the transmitting medium is the same, the method of transmission is the same, as in the case of light, but I think you will agree with me

that on this occasion I must not take up so wide a subject, but merely claim it as another domain of our science.

These few remarks, feeble and imperfect though they are, are put forward as a distinct claim of the important part which our science plays not only in the affairs of practical life but also in the more abstruse and recondite speculations which lie in the very forefront of scientific development. In insisting, however, on the recognition of the proper position of optics I do more, for, if need be, I desire to instil into the minds of the rising generation of Opticians a feeling of pride in their work and of boundless confidence in its importance and possibilities. Indirectly, too, I justify the existence of the Optical Society, whose career, I venture to hope, will always be worthy of, and tend not a little to advance, the splendid science from which it takes its title.

THE CENTRING OF SPECTACLE LENSES.

By Mr. W. A. Dixey, *Member*.

Read before The Optical Society on March 22nd, 1900.

IN dealing with the subject of the centring of spectacle lenses, it is necessary at first to define what we mean by the centre of a spectacle lens. Because throughout this paper I intend to disregard the thickness of the lens, and the position of nodal points. They do not affect the problems which the subject will present; and for our present purpose we may define the centre of a spectacle lens as that part of the lens through which light passes without deviation; or, more exactly, the centre of a spectacle lens is that part of the lens through which a normal ray of light passes without deviation.

It may also perhaps be as well to define one or two other terms of which I have made use in the course of this paper. In passing through any part of a spherical or cylindrical lens other than the centre, light is bent out of its course. This bending quality of a lens is alluded to as *prismatic effect*; and the alteration in the course of the ray of light is referred to as its *deviation*. There is another aspect of the same fact which requires its special word. If an object is looked at through the edge of a lens its apparent position is altered. This alteration in the apparent position of an object I call *displacement*. So that there are these three terms, prismatic effect, deviation and displacement, which are all different aspects of the same thing; prismatic effect referring to the quality of the lens, deviation to the effect on the light, and displacement to the apparent effect on the object. I may also note that in dealing with an oblique displacement, or a deviation in an oblique direction, I have generally found it convenient to resolve the obliquity into its horizontal and vertical elements. This is particularly useful in treating of spectacle lenses, as there is so much difference between the action of the muscles which control the horizontal movements of the eyes and those which control their vertical movements.

Let us take some ordinary spectacle lenses to illustrate our definition of the centre.

Fig. 1 represents a convex spherical lens with vertical and horizontal sections. It is clear from the shape of the horizontal section that all light passing through it must be bent either to the right or to the

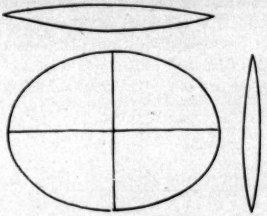


FIG. 1.

left, except in the thickest part where tangent lines would be parallel. And this would be true whether the section were made through the middle or above or below it. In respect, then, of horizontal deviation, we can see that the vertical line on the plan represents the position of no deviation. Similarly if we look at the vertical section we shall

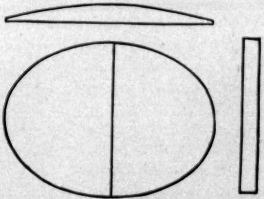


FIG. 2.

see that the locus of no up or down deviation is the horizontal line. It is clear then that if the vertical line represents that part of the lens where there is no lateral deviation, and the horizontal line represents that part where there is no up or down deviation, the only part of the lens where there is no deviation at all is the point where these two lines cross. That is the centre of the lens.

Let us take the case of a plane cylinder. Fig. 2 shows such a lens

with a vertical axis. This is much simpler, because it is evident there is no up and down deviation, and the place of no deviation is the apex of the cylindrical curve, which is represented by the vertical line in the figure. Here, then, the centre is not a point but a line.

And let us note, for this is important, that the centre is a vertical line only when the axis of the cylindrical curve is vertical. But when that is oblique, then the centre of the lens is also an oblique line.

Let us see how this oblique axis affects the lines of no deviation when the cylinder is combined with a spherical lens. Take a lens sph. + 2·00 cyl. + 2·00 ax. 45°. We have seen that so far as the

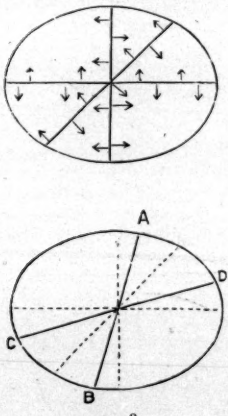


FIG. 3.

spherical lens is concerned, the lines of no horizontal and vertical deviation are represented respectively by the vertical and horizontal lines; also that so far as the cylindrical lens is concerned the line of no deviation coincides with the principal axis of the cylinder. The upper oval in fig. 3 shows these lines and the arrow heads indicate the directions of the displacements caused by the spherical and the cylindrical curves. It is clear that in parts of the lens the displacements or the deviations due to the two components of the lens are in the same direction, and the deviation is therefore increased; but in

others the two lenses act in opposition, and the deviations are therefore neutralised. The result is shown in the lower oval of fig. 3. The locus of no horizontal deviation is a line lying between the vertical line and the axis of the cylinder, represented by the line A B; and the locus of no vertical deviation lies between the horizontal line and the axis of the cylinder, and is shown as the line C D in the figure. The centre of the whole lens is the point of intersection of the two lines, but it is important for the due appreciation of certain problems connected with spectacles to recollect the condition of lateral and vertical deviation in other parts of the lens.

Fig. 4 shows another lens sph. + 2·00 cyl. − 3·00 ax. 60°. Here the cylindrical displacement is in the reverse direction, *i.e.*, towards the axis. The locus of no horizontal deviation is found on the other

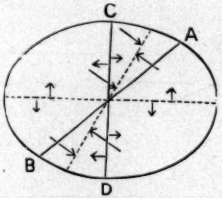


FIG. 4.

side of the cylinder axis. Its position may be best estimated by resolving the oblique 3 diopter deviation into a 2 diopter horizontal and a 1 diopter vertical deviation, This is accurate enough for our purpose, as the axis is 60°, though not quite exact. Then the line of no vertical deviation will coincide with the minor axis of the oval, along which the normals to the cylinder axis and the major axis of the oval are in the ratio of 1 : 2. But we need not puzzle too much over these diagrams, because, as I intend to show you shortly, these lines of no deviation are easily found empirically, and with quite sufficient accuracy for spectacle work.

Having now illustrated what I mean by the centre of a spectacle lens, I want to direct your attention to the consideration of spectacle lenses taken in pairs. I suppose we all of us, when talking loosely, use some such phrase as "the eye should look through the centres of the lenses." The words convey the idea, perhaps, with sufficient accuracy for most purposes, of what we ought to aim at in spectacle fitting.

But clearly it is not an exact expression. The eyes range over the whole of the lenses; and it would be more precise to say that spectacles should be so arranged that the eyes look through corresponding parts of the lenses, where the displacement, due to prismatic effect, is equal and in the same direction. Now, it is evident that these conditions are only possible when the two lenses are of equal power, and, in the case of cylinders, in a similar position. When we come to consider the rule as applied to most cases of oblique astigmatism, or to cases of anisometropia, we are met with a difficulty.

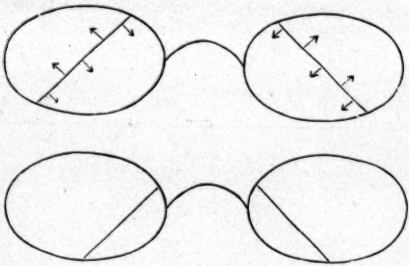


FIG. 5.

Let us take a simple case of oblique astigmatism. A pair of spectacles, as represented in the top diagram of fig. 5, is fitted with lenses

R. cyl. + 1·00 axis 60°
L. cyl. + 1·00 axis 120°

If you look at the diagram you will see at once the difficulty that arises. The straight lines represent in each eye the centre of the lens, or that part of the lens where there is no prismatic effect. The arrow heads show the direction of displacement, due in each lens to its cylindrical curve. There is only one possible position where displacement is equal and in the same direction, viz: when the eyes look through the geometrical centre. If they look above, the centres are too narrow; if below, the centres are too wide; if they look to the right, the displacement of the right eye is obliquely upward, of the left obliquely downward; if they look to the left, the displacement of the right lens is obliquely downward, that of the left lens obliquely upward.

It is important to note that this displacement increases as the part of the lens through which the eyes look is further from the centre; and that its rate of increase is greater the deeper the curves of the lens.

We can examine this better in dealing with our next case, a case of anisometropic myopia. Let us take the spectacles as

R. sph. − 2·00
L. sph. − 6·00

the diagram shows the spectacles in horizontal section and in plan. Here again you will see that the only part of the lenses when the displacement is equal is in the geometrical centres; for there in both lenses the displacement is = 0. Now I want you to see that in the weaker lens the prismatic formation to which the displacement is due is much less marked than in the stronger one; and also that while near the centre

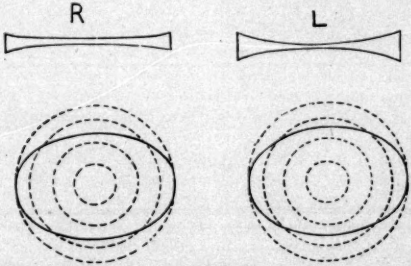


FIG. 6.

The prismatic effect is slight, as we approach the margin it becomes much more marked. If we take four distances, 5, 10, 15 and 20 millimeters from the centres of the lenses, which distances are represented by the circles, we shall find that for the − 2·00 lens the prismatic effect

at 5 mm = 35′
10 „ = 1°9′
15 „ = 1°48′
20 „ = 2°18′

while for the − 6·00 lens it is

at 5 mm = 1°43′
10 „ = 3°26′
15 „ = 5°9′
20 „ = 6°51′

So that if the eyes be directed 5 mm. to the right, there is a deviation of the right line of sight of 35′, and of the left of 1°43′; while the respective deviations for the right and left lenses at a distance of 20 mm. from the centres are 2°18′ and 6°51′.

What is the remedy for this? Clearly there is no complete remedy. I have said elsewhere spectacles are always a compromise. Every possible pair of spectacles presents certain insurmountable difficulties. But mitigations are possible; and it is not the least fascinating part of the craft of the Spectaclemaker to discover and apply these mitigations.

In the first place much may be done by judicious decentring. I hope later on to deal with some of the principles which may safely guide us. But look for a minute again at fig. 5, and see what decentring will do for us here. As it is you will recollect that throughout the upper halves of the lenses the centres are too narrow, and in the lower halves too wide. Now, suppose we decentre each lens 1 cm. inwards, as in the lower diagram. The centres are now nowhere too wide. In parts certainly they are too narrow; but that, as I will explain later, is a lesser evil. That is an instance of what can be done by decentring.

Another method of mitigating the bad effects of unequal displacements is by using small glasses; preferably shallow shapes; *e.g.*, ovals with a short minor axis, or ovals with the top half cut off. By this means you abolish the greater differences of prismatic effect at the margins; and especially by the shallow shapes you reduce them in the direction where they are least tolerated. In this connection I would call your attention to the value of Franklin and bifocal spectacles, in which the lenses must necessarily assume this shallow shape. There are many different ways of combining the two lenses in Franklin spectacles, and they are all equally suitable to this purpose with one exception. I make an exception of the worked bifocal, where the two lenses are ground on the same piece of glass. This form of bifocal should never be used in cases of anisometropia such as we are considering, because it is impossible to work the glass with the centres in the middle of the lenses. The lenses are therefore what we may call marginal, and the differences of vertical prismatic effect are increased. Of course these objections only apply to the special cases we are considering. In some cases the worked bifocal may be the best form of Franklin lens.

For the same reason care should be exercised in fitting cemented

bifocals that the added lens is so centred and set as to neutralise the vertical prismatic effect due to its position on the margin of the large lens. This requires careful calculation and adjustment, and unless it is done the cemented bifocal is as unsuitable for these cases as the worked bifocal.

Of the many forms of Franklin spectacles, I myself give preference to the two separate lenses with a straight division between them; largely for the reason that there is then no difficulty in arranging the centre in the middle of the verticle axis of each lens. Another advantage that attaches to this form is that it facilitates a difference in the width between the centres of the upper and lower halves; we shall see later on that this is generally desirable. I may add that a further point in its favour is that it permits the tilting of the lower lenses, which is a very important advantage, though the reason why it is so does not come properly into the present paper.

Now I want to take you back again (see fig. 6) to the case of anisometropia, where the correction was

R sph. — 2·00
L sph. — 6·00

I called your attention before to the great difficulty that is involved in a pair of spectacles fitted with such lenses. The basis of the difficulty is the desire of the eyes to fuse the two images which they receive. This fusion occurs only when the images fall upon corresponding parts of the retina. The efforts of irregular convergence which the eyes make in order to ensure this effect are involuntary; they cannot be controlled; and in looking through spectacles such as these, these irregular efforts must be constantly exercised in all directions. For instance, as the eyes range from the centre upwards, they pass first through an area, where the difference of displacement is very slight, and can be corrected perhaps with little inconvenience; at a distance of 10 mm. from the centre the difference of displacement is equal to that which would result if a prism of 2° 17′ were held base up in front of the left eye. At 15 mm. the difference of prismatic effect is $=3\frac{1}{2}°$; strong eyes can still perhaps fuse the images, but the strain is so great that after a few seconds the muscles are over-tired and give way, with a result that the images separate. At 20 mm. fusion is no longer possible and diplopia supervenes. So much for one direction. It will be seen that if the eyes range down instead of up, the same efforts are necessary but in an opposite direction; while if they travel to the right they must unduly diverge,

and if to the left, converge. Thus the whole gamut of strain is sounded, and the extreme effort of every muscle is more than demanded. I have been led to enlarge upon this subject, because I regard it as one of the most difficult problems with which we Spectacle-makers are confronted. Many suggestions have been made for the treatment of these cases. Evidently the treatment must depend on considerations of the age, health and habits of the spectacle wearer; on the existence or non-existence of binocular impression, and so on; considerations which are certainly not germane to the subject of the present paper, and which, moreover, in my view, lie outside the proper province of the Optician.

But I want to call your attention to a suggestion which I made some five years ago for treating such cases with what I have called concentric bifocals. I have already pointed out that the greater prismatic differences exist only in those parts of the lenses which are further removed from the centres. My proposal is to reduce the size of the stronger glass in myopia, or the weaker in hyperopia, so that

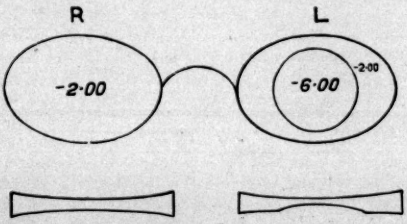


FIG. 7.

the difference in prismatic effect of the extreme margin of the reduced lens and the corresponding part of the other lens does not exceed what can easily be corrected. Upon the remaining surface of the bifocal lens I propose to work the curve of the other lens.

The figure which illustrates our case of anisometropia treated in this way explains my suggestion better than words. With spectacles so arranged, each eye being fully corrected, easy binocular sight is obtained through the central and effective part of the lenses; and if the sight is directed through the marginal part of the lenses, there is at least no strain from difference of prismatic effect; both images,

though only one is clear, falling naturally on corresponding parts of the retina.

This method has been tried and adopted with success by several Oculists, and I venture to commend it to those of you who are bold enough to do your own refraction, as a safe way of dealing with these difficult cases.

As some relaxation before entering upon the second part of my paper, the effect of centring upon the conjugate movements of the eyes, I propose to demonstrate the different methods of finding and marking the centres of spectacle lenses.

1. By reflection.
2. By finding points of no horizontal, and of no vertical deviation.
3. The Maddox analyser.
4. The Dixey Prismeter.
5. A new centring instrument.

Perhaps it may be asked, why it is necessary to be so minutely particular about the centring of spectacle lenses. The eyes have an extensive power of adaptation, and so long as a rough accuracy is attained, will adjust themselves to any slight difference of displacement. And the answer is, that in these minute differences of displacement are often involved the whole difference between comfort and discomfort, between ease and pain, between a beneficial and an injurious effect of the spectacle lenses upon the eyes. And what especially makes the matter worth studying is that in some directions a wide difference of displacement is allowable, and, indeed (as we shall see) desirable; while in other directions a very small difference of deviations is attended with pain and distress.

Now in approaching the consideration of the pathological aspect of the conjugate movements of the eyes, we trench on difficult ground. I cannot leave it out of account in dealing with the centring of spectacle lenses; but I will say frankly that in many of the problems connected with the subject I have no conviction, nor have I the knowledge which I should consider necessary before giving a trustworthy opinion.

In such a case one generally turns to authority; but the authorities on this subject are notably barren. You will find in the text books plenty about normal movements, and something about abnormal movements, but, so far as I can discover, there is very little about the pathology of abnormal movements, as distinguished from morbid con-

ditions. Nevertheless, there are certain propositions, I mean to lay four before you, which, based as they mainly are on common sense and common experience, I think we may conditionally accept as guides in our practical work of spectacle fitting.

But before I attempt to formulate these more or less debateable propositions, let us examine two or three points connected with the conjugate movements of the eyes which are merely matters of demonstration. Let us consider the conditions of normal convergence.

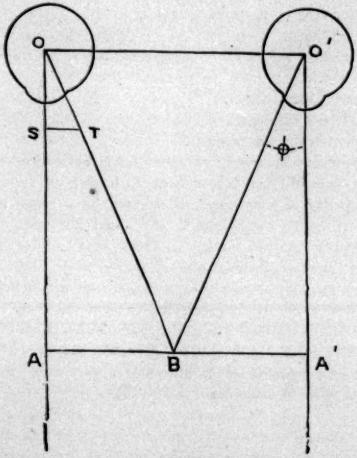


FIG. 8.

Starting with the eyes at what we may call the position of rest: both eyes are directed to a point at infinite distance, the visual lines are parallel, and remain so, as the eyes turn about in their sockets; but only so long as the objects looked at are at an infinite distance; if a near object is looked at, the eyes turn inwards, and the lines of sight converge. We have this represented in fig. 8.

OO′ represent the centres of rotation of the two eyes. The parallel lines OA O′A′ represent visual lines when the object is at infinity. B

is a near point at short reading distance, a quarter of a meter, to which the eyes converge along the lines OB O'B'. We will take pupil distance at 60 mm.; then we have

$$AB = 30 \text{ mm.}$$
$$OA = 250 \text{ mm.}$$

and tan ϕ, the angle through which each eye turns in converging,

$$= \frac{30}{250} = \cdot 12.$$

or, $\phi = 7°$.

It is evident then that each eye turns through an angle of 7° in converging to an object at ordinary reading distance. This is our first point, and is simply a quantitative statement of the normal exercise of the function of convergence.

The second point to which I would call your attention is illustrated by the same figure:—In converging sight the distance between corresponding points on the visual lines varies inversely as their distance from the centres of rotation of the eyes.

This is a matter of great importance in its application to spectacle fitting. Spectacles that are arranged for use at a definite distance, as for reading, should always be centred with this condition of the visual lines in view; and it will be interesting on this account to arrive at some quantitative estimate of the amount of decentration required. The point S on the figure represents the position of the spectacle lens in front of the eye. Unfortunately, the distance of S from O cannot be measured. I take it in an average case as 20 mm. It must always be estimated. In extreme myopia it will be greater, in hyperopia, less; long lashes or a particular formation of the nose may increase it. But taking O S as 20 mm., we have

$$S T = 20 \tan \phi$$
$$= 20 \times \cdot 12 = 2 \cdot 4$$

which gives us 4·8 mm. as the difference in centering between distance and reading spectacles. It is easy to confirm these figures with the aid of what I call my gamma measure, which you will find on the table, and which anyone can make for himself. It consists of two discs with pinhole apertures pivotted together in such a way that the distance between the apertures is variable. Fixing the eyes on a distant object, hold the measure in the position of spectacles, and adjust the width till the two apertures appear to coincide; measure the

distance between them; then repeat the experiment with the object at reading distance: and the figures will be verified.

We may, therefore, take it as an established rule for spectacle fitting that the centres of reading spectacles should be about 5 mm. narrower than the pupil centres when the eyes are fixed at distance; *e.g*, if the pupil distance is measured as 60 mm., the reading spectacles should be centred 55 mm.

Now I want to call your attention to the next point, that centres can only be absolutely correct when spectacles are used at a definite distance. With spectacles for general use, as the eyes turn from one object to another, ranging over distances of from 6 ins. or so to infinity, the centres of the spectacles should also vary from 50 to 60 mm. For each distance between reading distance and infinity there is a corresponding value for the spectacles centres lying between 60 and 55 mm. Clearly spectacle lenses cannot be made to correspond with these differences. We must either centre the lens for distance, and be content to have them too wide for reading; or we must centre them for reading, and have them too narrow for distance; or we must find a mean. The consideration of this problem forces us on to the more difficult ground of the pathology of convergence.

I have said that I mean to submit to you four propositions, which, in my opinion, may be accepted as safe guides in our practice of spectacle fitting; and my first proposition is that *wherever possible the normal relation between convergence and accommodation is to be maintained*.

To illustrate the application of this rule let us take a simple case of presbyopia, represented by the formula R and L sph. + 1·00. Now, in this case, before the intervention of presbyopia, normal relations between convergence and accommodation have prevailed. With the 7° of convergence necessary for reading has been exercised an accommodation of 4 diopters. But so soon as you give the + 1 spectacles, you reduce the necessary accommodative effort to 3 diopters. This degree of accommodation has previously been associated with a convergence of not 7° but 5½°. The spectacles should, therefore, be so centred that the convergence at 250 mm. is reduced by 1½°. With convex lenses this means a decentring inwards in addition to the similar decentring due to the position of the spectacles on the visual lines. With concave lenses the allowance takes the form of an outward decentring, and it will be seen that it occurs in an opposite direction to the allowance for position on the visual lines, which it may

either exactly neutralise, or over or under neutralise, according to the strength of the lens.

In cases of hyperopia and myopia when the same strength of lens is used for two distances, normal relation of convergence and accommodation may be maintained by the use of what I have called bicentric spectacles; *i.e.* spectacles, each eye of which consists of two lenses as in bifocals, but with each lens so centred that among other things allowance is made for convergence.

I suggest this as a general rule, but it must be applied with discretion, as it is evidently subject to modification. In the case of an adult with a slight error of refraction, who has not habitually worn spectacles, it is clear that habit will have interfered with the normal relation between convergence and accommodation. Take the case of a myope of 2 diopters. He will have the habit of converging up to half a meter without exercise of his accommodation, and for reading at 250 mm., he will only require 2 diopters. Similarly a hyperope will accommodate without converging, and will require more than 4 diopters of accommodation in converging to 250 mm. In such cases a modification of the rule may be allowed, but how far this concession to habit should extend, or whether an effort should not be made to restore normal relations, are precisely questions on which I have no conviction. They may be further considered in connection with my third proposition.

My next proposition is that *artificial convergence induces accommodation*. There is no doubt of the converse, and in view of the close inter-relation of the two functions, it seems possible to assume that either may be stimulated by the other. Whether this is so or not, our practice in centring spectacle lenses is not materially affected, because if the assumption is right, it would only confirm the rule, which may be briefly indicated as "convex in and concave out," for which we have already ample reasons; and if it is not right, it need not be considered, and our other reasons are not affected. But if we may assume that this proposition is correct, we can claim for the judicious application of the rule to the centring of spectacles an importance of great weight. It will be admitted that among the therapeutic properties of spectacles, one of the chief is to limit undue accommodation. It is clear that, if our proposition holds, by reducing convergence we tend to check undue accommodation. Thus the practice we advocate for other reasons acquires additional value from the therapeutic point of view.

There remain two propositions which deal respectively with dissimilar deviations in a horizontal and in a vertical direction; and my third proposition dealing with horizontal deviations is that *slight divergence is not painful or injurious, but excess of convergence is injurious and to be avoided.* I can give you no reasons without getting beyond my depth. But I do not think that the proposition will be questioned by anyone with practical experience. I have already demonstrated the extent of normal convergence, which amounts to 14° taking the two eyes together at an ordinary reading distance; and on the point of the injurious effect of excessive convergence authority speaks very clearly. Slight divergence may I think safely be defined as 1° for each eye. I do not think this should be exceeded unless the nature of the lens demand it. Referring back then to the problem which I left unanswered, how to centre lenses which are intended for general use; we are in a position to lay down that the lines of sight must never at a working distance pass through the diverging parts of the lens, *i.e.*, through both nasal sides, of convex, or both temporal sides of concave lenses, while, if the nature of the lenses demand it, the lenses may be so centred that for distant sight the visual lines *may* pass through the converging parts of the lenses, provided always that the prismatic effect does not exceed 1° for each eye. This you will see is a further confirmation of our rule, convex in, concave out.

The fourth and last proposition on the subject of conjugate movements is that *difference of vertical deviations is painful, and injurious; and is by all possible means to be avoided.* This again is a proposition which will assuredly not be questioned by anyone with experience, and in its application to spectacle work, is of the first importance. When the lenses allow, the centres should be set with the nicest accuracy, so that vertical displacements are similar in corresponding parts of the lenses. Frames should be designed so as to sit straight, as it is evident that with nearly all lenses the slightest degree of obliquity in the position of spectacles or eyeglasses will cause difference in the vertical deviations. In those cases where the nature of the lenses prevents similarity of vertical deviation, every possible means should be adopted for limiting the differences. I have already made certain suggestions in this respects, and others will be found in the text books.

In considering these problems connected with the conjugate movements of the eyes it has been my endeavour to confine myself to that part of the subject which is associated with the centring of spectacle lenses.

Questions of muscular insufficiency, all the phorias and the tropias lie outside the subject of the paper as I conceive it. Nor have I any object but to put before you, as clearly and exactly as I can, those qualities of lenses, and those conditions of the conjugate movements of the eyes, which should be, and indeed more or less must be, in our minds whenever we sit down to consider where we shall put the centres of our spectacle lenses. This clearly lies within the province of the Optician. But we must distinguish between these necessary and desirable adjustments of the centres, and adjustments that may be said to involve treatment. As I have tried to emphasise; whatever general rules we make, in adapting them to individual cases there are many considerations involved, the right decision of which demands medical knowledge and experience. I think we Opticians will best fulfil our functions if we confine ourselves to suggesting the possibilities of lenses in their different forms and adjustment, and, so far as our practical work goes, if we limit ourselves to the observance of the obvious conditions which it has been the object of this paper to indicate.

THE PRINCIPLES OF FOCUSING AND LENS MEASUREMENT FROM A PRACTICAL POINT OF VIEW,

A Lecture by Thomas H. Blakesley, M.A.,

At a Meeting of the Optical Society, on June 21st, 1900.

ALLOW me, Sir, at starting, to express my thanks to your vice-president, Professor Silvanus Thompson, for being the means of introducing me to the Optical Society, and to the Council of the Society for affording me this opportunity of submitting certain views which I hold very strongly, and which I believe to be of great importance in the practical uses of lenses. These views, I regret to say, have the disadvantage of novelty, and must, I am well aware, encounter the opposition inevitable in such case from those who have become handy in the practice of a system which, in the absence of a better, has become entitled to be called the best.

The reforms which I desire to see, apply not merely to the employment of lenses, but to the statement of those characteristics of a lens which, usually given by the seller, are of importance to the user. It is this double character which makes such a reform all the more hard. A manufacturer will say, What is the use of giving data, of which the employer does not know the use? A buyer will say, What is the use of a system which the manufacturers do not give you the data for employing?

Every instrument of science has an aim in view. The aim of a lens is to produce well focused images of some given relation as regards size to the objects presented to them.

The aim of a thermometer is to give the temperature of its surroundings. Suppose a very well-made thermometer without a scale. Its aim would hardly be considered attained, but it might become useful in the hands of those who could give it a scale. Suppose it to be graduated but not numbered. Its usefulness would be increased. Differential measurements may be taken by means of it, and in the

hands of some one who can experimentally determine the value of some one to its divisions, it would rise a step more in usefulness.

Now a lens system of which nothing more is known than that it is convex or concave, is closely analogous to a thermometer without a scale, and a lens of which the focal length is alone given, is like a thermometer graduated, but unnumbered.

A similar analogy might be drawn between a lens and any other instrument of precision; but it is unnecessary to dwell more upon this point than to say that it appears to be a general rule to furnish as much information with an instrument as will render it most useful to the employer. Probably it is to the interest of all concerned that this should be so.

But lenses form a notable exception to this rule. I have never seen a pretence of affording more information with a lens system than the focal length, and even this is often given most imperfectly.

The common lens formula with which writers and practical users are wont to content themselves is known to be merely an approximation, and is, moreover, of a very inconvenient form. It could only be strictly true for a lens of indefinitely small thickness, which is never the case. For simple lenses, as contrasted with combinations of lenses placed at some distance from each other, it is nearly true, but not sufficiently so that the focusing cloth can be safely discarded in cases of photographic enlargements and the like. The focusing cloth in such cases is the confession of approximation, the veil of inaccuracy.

Still less is the common formula applicable when lens combinations of very considerable thicknesses are employed, as in the object glasses of microscopes, the better lenses employed in photography, and the combinations used for lantern projection. Directly the combinations become of definite thickness the statement of the value of the focal length alone is an imperfect and misleading exposition of the focusing properties; valuable to a certain extent no doubt, but needing to be supplemented by other facts. For focusing these additional facts are two in number, and they are positions, not lengths.

There is a very general proposition true not merely of single lenses, but of all systems of lenses upon the same axis which I wish particularly to emphasise on account of its simplicity and utility, and on account of its general neglect in text books. I do not in fact know of any book in which it is described.

A second proposition, which I shall describe afterwards, is of equal utility with the first and consists in a method of finding

the general properties alluded to in the first proposition for combinations of systems, when they are known for the individual systems.

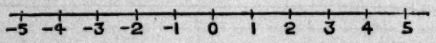
In neither case shall I weary you with mathematical proofs and formulæ, my object being to simplify the conception of lens actions, rather than to discover ingenious and useless properties of combined mathematical formulæ.

The true view to take of what is called the focal length of a lens is that it is a certain characteristic length having the following important property. The lens being fixed in space, but the object, supposed small, being movable along the axis of the lens, the magnification of the image and its position along the axis change *pari passu*.

The magnification is the relation which any line in the image bears to the corresponding line in the object, and change of unity in the magnification corresponds with a change in the position equal to the focal length.

Thus the focal length is the change in position of the image corresponding to a change of unity in the magnification.

We may suppose numerals placed against the points of the line constituting the axis of the lens indicating the magnification at the various points. These numerals will form a regular scale; that is, any two points situated at a constant distance one from the other will be positions where the magnifications differ by the same amount, and that difference in magnification will be the ratio which the constant distance bears to the focal length.



Suppose on such a scale we contemplate the numerals in descending order, we shall at last arrive at the zero of the scale. This implies that the size of the image vanishes as compared with that of the object. It is clear that at this point is the principal focus of the lens.

If we pass this point and continue in the same direction the numerals will still algebraically decrease, or arithmetically increase with change of sign. We must, therefore, distinguish between the points + 8 and − 8. In two such cases the positions of the image are relatively inverted, and we require some convention to distinguish the two cases. I have adopted the following. If the image is in-

verted relatively to the object, let the minus sign be applied, and if not let the plus sign obtain.

We may thus divide up the axis into a scale running uniformly from $-\infty$ to $+\infty$ and interpret the character of the image at any point.

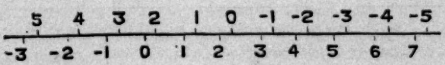
At the point marked say -3, if an image is formed, then it will be inverted as regards the object wherever that may be, and of three times the scale linear.

At the point marked $+3$ an image would be erect as regards the object and three times its size line for line.

Now, taking into consideration the fact that if an object is made to take the exact position and shape of the image in any given position, and light were transmitted backwards from it through the lens, its image would necessarily coincide in position and shape with the original object, it becomes manifest that the axis may be again similarly divided up and numbered in a series whose numbers interpreted in the the same way refer to the size and character of the object relatively to the image. The spacing between the integral numbers will still be the same, but the numbers will run in the reverse order to the others, and the integral points will not necessarily coincide with those of the first series.

In this statement the medium (generally air) is supposed to be the same on either side of the lens. If this be not the case as in a lens-system employed at one side to investigate subaqueous matters the spacing will be different, but this case, though extremely interesting, is not contemplated in the present paper.

We may thus graduate the axis by two scales, one for the object, or more exactly for light before encounter with the lens, with numbers



and divisional marks *above* the axis, the other for the image or for light after passing through the lens with similar numbers and marks *below* the axis, as in the diagram.

The interpretation according to the numbers allows us at once to give conjugate points.

Suppose the object at any point. The number on the upper scale (say -3) where it is situated gives the relative size of the object to the image. The inverse of this number ($-\frac{1}{3}$) gives the relative size

of the image to the object, and the position on the lower scale at which the image will be found. If the lens is what is generally called convex the numbers for the object scale will increase algebraically in the direction of the light propagation, and for the image scale in the opposite direction.

The opposite character of lens, called concave, will have the object scale increasing algebraically in the direction opposed to the light propagation, and the image scale increasing algebraically in that of the light propagation.

This constitutes the real distinction between lens systems, and though the words convex and concave must be retained in a country which was 200 years in adopting the Gregorian Calendar and has not yet adopted the Metric system, the words have small reference to the surfaces in lens system. The day eyepiece of an ordinary telescope is as concave optically as the eyepiece of a Galilean telescope, and therefore gives the corresponding effect of erect representation.

In a thin simple lens the two points + 1 of the two scales may nearly coincide, and are considered in coincidence in the approximate formulæ in customary use.

They only really do so coincide in simple lenses when the surfaces are concentric, however far they may be situated from each other. To rigorously fix upon conjugate points, therefore it is necessary to know,

(1) The distance of some number (0 recommended) of one scale from some point of the lens (the centre of the surface of first encounter recommended).

(2) Ditto, ditto for the other scale, the surface of last encounter being recommended.

(3) The focal length, depending for sign on the directions of the scales, and generally taken as negative for convex and positive for concave lenses.

The approximation referred to above, as in vogue for simple lenses, becomes absolutely absurd and inapplicable with lens combinations, but the rigorous rules I have described hold in all cases.

A lens combination may therefore have its focusing properties registered in a diagram of memorandum of great simplicity as below, in which I have taken actual cases from my own notebooks :—

$$< \cdot 463 \; \{ 3 \cdot 77 \; \{ 1 \cdot 865 > \quad f = -3 \cdot 420$$

Nominal 1½″ Object glass of Microscope at the R.N.C.

$$< 16{\cdot}40 \left\{ \begin{matrix} 7{\cdot}45 \\ f = -17{\cdot}81 \end{matrix} \right. \frac{1}{+} 10{\cdot}45 > \Big\} \text{ Lantern Objection.}$$

$$< 11{\cdot}3 \frac{1}{+} {\cdot}7 \frac{1}{+} 12{\cdot}8 > \Big\} \begin{matrix} \text{Achromatic} \\ \text{Enlarging Lens.} \end{matrix}$$
$$f = -12{\cdot}185$$

The distances are all centimeters.

Thus the data relating to each ns, which will make it thoroughly useful, are—

The positions of two principal foci relatively to the lens and the algebraic value of the focal length.

The best and easiest way of determining the positions of the principal foci, when these are outside the lens system, is to place the system vertically upon a piece of plane mirror, and adjust by trial a piece of sharply cut white paper held in any convenient form of universal holder, till it coincides with its own image formed by light which has passed through the lens, has been reflected at the plane mirror and again passed through the lens. The coincidence of image and object in such cases is a criterion of the point being the principal focus, and may be practically determined to a very high degree of accuracy, with the help of a short focal length hand-lens, by any one accustomed to observation and acquainted with parallax.

The focal length of a convex system may be determined by the use of the idea connecting it with the magnification forming the first part of this paper.

If a negative photograph is taken of a well drawn scale of lines and from this two positives on glass are printed, these will necessarily be of the same size. If one of these is used as an object and its image be clearly focused upon the film of the other, coincidence being secured by adjustment with the help of a hand-lens, the magnification may be at once determined by comparing the scales image and real seen upon the film.

This measurement may be checked at the other film.

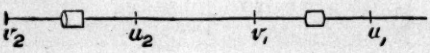
A second position may then be found with its second magnification.

If the lens system has been stationary, the change in the position of a film divided by the change observed in the magnification will be the focal length. This method admits of indefinite checks.

The second proposition which I have mentioned is the following:

Suppose we have two lens systems, whose elements, as described

above, have been accurately determined, and these two systems are placed coaxially, to determine the new elements of the whole combined system.



Suppose u_1 v_1 the principal foci of the first system, and u_2, v_2 those of the second system. Then these points are all on one straight line, the common axis. Suppose k the distance from v_1 to u_2, positive in the direction of propagation of the light, and suppose f_1 and f_2 the two focal lengths. Then the new first principal focus will be situated at a distance from u_1 in a direction opposed to the propagation of the light, equal to

$$\frac{f_1^2}{k}$$

The new second principal focus will be situated at a distance from v_2, in the direction of the propagation of the light, equal to

$$\frac{f_2^2}{k}$$

The new focal length will be

$$\frac{f_1 f_2}{k}$$

These curiously simple rules are sufficient for the purpose of the proposition, and enable one to see with remarkable readiness the general results of such combinations, *e. g.*,

(1) The motion of the first principal focus due to the application of a second system depends only on the first system and on k, and the direction of that motion is only dependent on k.

(2) If the systems are both concave or both convex, the character of the combination in this respect depends entirely upon k.

(3) Two thin convex lenses of equal focal length and separated from one another by a distance equal to that focal length, will form a combination having the same focal length, but the principal foci are coincident with the lenses.

This proposition is most invaluable in determining the elements of a

combination where a principal focus may be inaccessibly placed within the system, as in the case of the Huyghen's eyepiece. It has a useful application in the day eyepiece of a telescope, which, I have remarked, is really concave in character.

I have also found it most useful in actually determining focal lengths after the principal foci have been fixed, in a way I have described in a paper read before the Physical Society.

A SIMPLE DIRECT METHOD OF TESTING SPHERICAL AND CYLINDRICAL LENSES.

Paper by Mr. C. V. Drysdale, B.Sc., *Member*.

Read before the Optical Society, on June 21st, 1900.

ALTHOUGH there are at present a considerable number of methods for testing the focal length and other properties of lenses, there yet seems to be room for one which should be universally applicable to all kinds of lenses or lens systems, whether spherical or cylindrical, positive or negative. In order to be of value commercially also, the method should be easily understood and require no calculation. In the present paper such a method will be described, and although it cannot be said to involve any new principle, and is of the simplest possible character, it is hoped that it will not be without interest.

Before describing the new method it may be well to say a word or two about the methods of lens testing most commonly in present commercial use. The favourite one of these appears to be that of neutralisation, as most Opticians have at their disposal a trial case of standard lenses; and the method is fairly simple and accurate for thin spherical lenses. In the case of cylindrical and sphero-cylindrical lenses, however, neutralisation is troublesome, and not very accurate, as it is somewhat difficult to insure the exact coincidence of the axes of the trial and standard cylinders; while it is of course useless in the determination of the equivalent focal length of thick lenses or lens systems such as are required in photographic and other optical instrument work. The Spherometer or its substitute, the Geneva Lens Measurer, is also frequently used, but as the value of its readings depends upon the refractive index of the lens, and it is also useless for thick lenses, its use is even more restricted than that of neutralisation. Beyond these a number of special methods are used for specific purposes, such as photographic lens testing, etc., but there can hardly be said to be any one method which meets with universal acceptation.

PRINCIPLE OF THE NEW METHOD.

As was mentioned above, the principle of the method here to be described is exceedingly simple. A simple convex spherical lens A., fig. 1, of convenient but unknown convergence, is placed in front of a screen B. at some greater distance than its focal length; there will then be some point C. which is conjugate to the screen with respect to the lens, and whenever an object is placed at the point C. a sharp image of it will be produced on the screen. If the lens to be tested

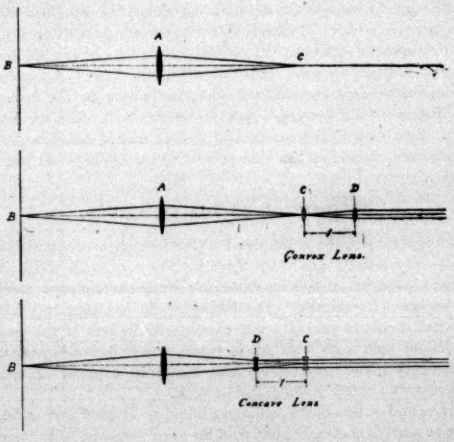


Fig. 1.

D. is mounted in front of the former lens and moved until a mark on its surface is focused on the screen, it will of course be at the point C. Now, if the lens D. is moved away from or nearer to the lens A. until its real or virtual focus F. coincides with the point C., it is clear that parallel light falling on D. will proceed as if coming from the point C. and will be focused on the screen. It therfore follows that if the lens to be tested has a mark on its surface first focused on the screen, and is then moved until distant objects are focused on the screen through

the combination, the lens will have moved a distance equal to its own focal length, in the case of a thin lens, or of its "back focus" in the case of a thick lens or lens combination. If the lens or combination is as a whole convergent, the motion from the first position to the second will be away from the screen, while if divergent the motion will be towards it. It is obvious that the focal length of the lens A. does not in any way affect the result, it is only necessary when testing a divergent combination that its focal length should be greater than that of the lens to be tested.

Although the method can be employed simply as described above, there are one or two obvious improvements which will increase its accuracy and convenience. The chief of these is to replace the screen B. by an ordinary eyepiece, thus converting the lens A. an eyepiece into an ordinary astronomical telescope, and giving us the increased sensitiveness of the focusing which one obtains with such an instrument. The other improvements will be best seen by reference to the actual arrangement that has been devised and which is before you this evening.

DESCRIPTION OF THE APPARATUS.

The apparatus consists simply of any ordinary form of optical bench, the quality simply depending upon the accuracy with which it is desired to work; for ordinary Optician's work the simplest possible wooden bench is suitable. The bench should be about two meters long, and should be provided with a scale with its zero in the centre, and divided both ways from this in centimeters or inches as preferred, with corresponding values of the convergence in diopters. A simple form of such a bench is illustrated in fig. 2.

At one end of this bench a simple telescope is fixed (an ordinary opera or marine glass will serve well for most purposes) with its axis parallel to that of the bench. The lens to be tested is mounted by suitable clips over an aperture in a plate supported on an ordinary sliding stand, fig. 3, the object of the plate being to cut off light which might pass by the side of the lens. The bench may either be turned towards some distant small source of light giving a practically parallel beam, or as this may be inconvenient from want of space, the usual device of a collimating telescope for producing parallel light may be employed. The collimator can of course be adjusted once for all by focusing the telescope for a very distant object and focusing the collimator to suit.

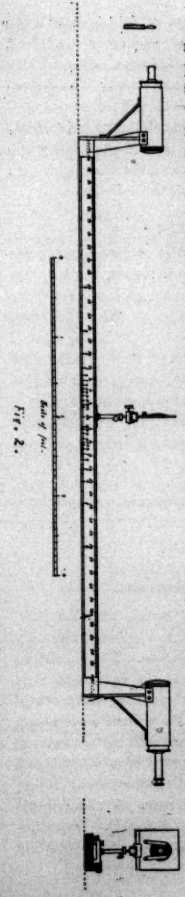


Fig. 2.

In testing any thin lens it should be mounted in the clips, above mentioned, and placed on the bench with the index of the stand at the zero of the scale; the tube or telescope should then be drawn out so as to focus on the lens surface (an ink spot on the surface is frequently convenient) and the lens then moved until the distant source of light or the aperture in the collimator is clearly visible. The reading on the bench will then obviously be the focal length of the lens, and its convergence in diopters is simultaneously given, no calculation of any kind being required. This of course applies to either thin convex or concave spherical lenses. In the case of lenses of a less convergence than one diopter the bench will not be sufficiently long, but if a single standard lens of 2 D. is kept for mounting in contact with long focus lenses, this presents no difficulty. This lens is shown in fig. 3, arranged so that it can be brought in front of the aperture. It will be well if we now describe *seriatim* the procedure in the case of different types of lenses.

Thin Lenses.

(1.) *Convergent or Divergent Spherical Lenses.*

Sufficient has already been said about the testing of the focal length of these lenses; the lens has its surface first focused and then its image of the distant object or collimator, diaphragm, and the focal length or convergence is directly given. A word or two will be said later on as to the centering and determination of the amount of de-centering of these lenses.

(2.) *Cylindrical Lenses.*

In the case of either convex or concave cylinders the procedure is exactly the same,

the only variation of the effect being that a line of light is seen when the focus is obtained, instead of a point. The reading of the bench when this line is sharp is the focal length or convergence, and if the eyepiece of the telescope is provided with a small circular transparent scale, the angle which this line reads on the scale will of course give the position of the axis, the line being parallel to the axis of the cylinder. In the case of testing spectacles, etc., if the glasses are always placed in the clip in their normal position, the reading in the telescope gives the ordinary angle of the axis of the cylinder.

(3) *Sphero Cylindrical Lenses.*

The effect is, of course, the same as in the last case except that two focal lines can be obtained; if both axes are convergent, the two foci will be formed when the lens is moved away from the telescope; if both meridians are divergent, the two foci will be on the same side as the telescope; while in the case of "mixed" sphero-cylinders the two lines will be on the opposite sides of the centre. In order to avoid the possibility of error it is well to number the divisions between the centre and the telescope with a negative prefix, while those between the centre and the collimator have a positive sign. The angles of the axes are, of course, given as before.

This includes all the types of thin lenses met with except bi-focal and other glasses where the refraction of different parts of the lens is different, the obvious course in this case is to cover the lens with suitable diaphragms and test each portion separately.

Thick Lenses and Lens Combinations.

The back focus or distance between the lens surface and the principal focus of any thick lens or combination is obviously given by following the same procedure as in the above cases. The important quantity, however, to be known in this case is the equivalent focal length, which is the distance between the nodal point of emergence of the light, and the corresponding focal point. By a small modification of the lens stand this quantity can be determined with equal ease.

The lens stand in this case is shown in fig 4, and consists simply of a V trough of any convenient material mounted on an ordinary sliding base, but capable of swivelling on a vertical axis. A small metal point should be provided which is in a line with this axis. In testing any lens combination the stand is first placed on the bench with its

index at zero in the ordinary way, and the telescope focused on the small point just mentioned; the point is then removed, the lens to be tested laid in the trough of the stand, and the stand moved until the focus is formed as usual. When this is the case if the trough is slightly rotated backwards and forwards about the vertical axis, the image in the telescope will generally be seen to move, but if the lens

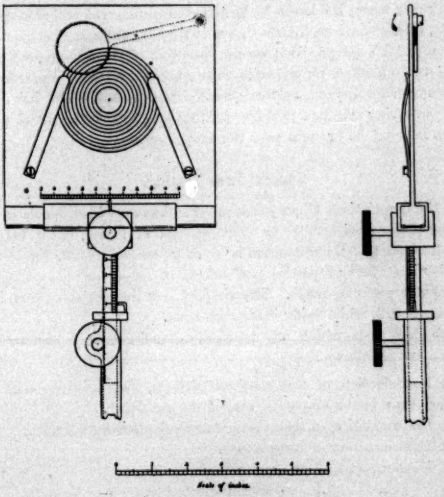


Fig. 3.

or combination is moved along the trough until its nodal point of emergence is on the axis, a rotation of some 10° or more on either side of the axis should produce no motion of the image. The lens can be easily moved until this point of no displacement is found, and the stand adjusted to retain a perfect focus in the telescope. The reading on the bench will now be the true equivalent focal length of the lens system whether convergent or divergent, since the axis is now at the

nodal point and the focus is formed at the point where the axis formerly was.

It may here be mentioned that it is obvious that no error is caused by the want of coincidence of the index on the lens stand with the surface of the lens or the axis, as the displacement is the same when taking both readings. This, of course, applies to both thin or thick lenses.

In cases where the lenses to be tested are numerous and of irregular shape, a lens stand such as is shown in fig 5 is rather more convenient. Two metal Y's are provided for the reception of the lens mount, and these are mounted on a bar in such a manner as to be separated by any convenient distance required for the lens tested. The bar itself slides in a ring attached to the swivelling axis so that the nodal point of the lens can be brought over the axis conveniently.

General Lens Testing.

In the descriptions above given mention has only been made to the testing of the focal lengths or convergences of lenses, but it may be well to show that the apparatus is equally convenient for the testing of other important properties and defects of lenses or lens systems if sufficiently perfectly made. The simplicity of the method is such that it seems worth while using it for such tests.

The chief tests which one required to make on any lens or lens system are as follows :—

(1) Examination of constructional defects, such as striae bubbles, etc., or strain in the glass, and also of the centering.
(2) Determination of the principal or equivalent focal length.
(3) Determination of its aperture.
(4) Measurement of its chromatic aberration.
(5) „ „ spherical aberration.
(6) „ „ distortion.
(7) „ „ astigmatism.
(8) „ „ focal volume and curvature of the field.

It would take too long to give a detailed account of the tests required in each case, and should hardly be necessary as no departure from ordinary methods is really involved, but a short reference will be made to each. It must be assumed in these tests that the telescopes are of sufficiently good quality and that they are set up in true alignment with the axis of the bench.

(1) Examination of Mechanical Defects.

Little need be said about the first part of this, such as the examination of the surfaces and quality of the glass, it is obvious that as the telescope is focused on the lens surface, which is well illuminated by the collimator, defects are distinctly visible. If strain is to be tested for, the use of Nicol prisms or other polarising and analysing arrangements in the two telescopes will at once locate the defect and give its position accurately.

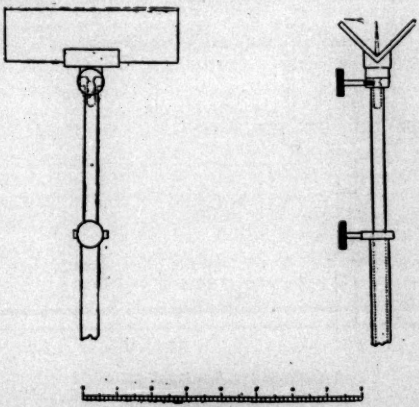


FIG. 4.

The matter of centering deserves a little attention. Of course it is obvious that we can only obtain the centering as a whole, the relative centering of the individual surfaces should be examined by Wollaston's method without any apparatus. If the axis of the lens or combination coincides with that of the bench the focus should appear on the centre of the webbed stop which should be used in the eyepiece of the telescope, and any displacement of the centre will be seen on a magnified scale. The centering in the mount can be tested by rotating the tube on its Y bearings above mentioned, and noticing whether the image revolves or not.

In the case of spectacle lenses the matter is of some interest as it is frequently desirable to test decentered lenses and to determine the mount of their decentration. For this purpose it has been found convenient to make the screen described for the reception of the lens in the first case with a number of circles concentric with its aperture, and to mount it on the stand so as to he capable of horizontal and vertical motion, and with scales for determining the mount of each. The glasses to be tested can be fixed in the clips with the lens to be tested set geometrically concentric to the aperture in the screen by the aid of the

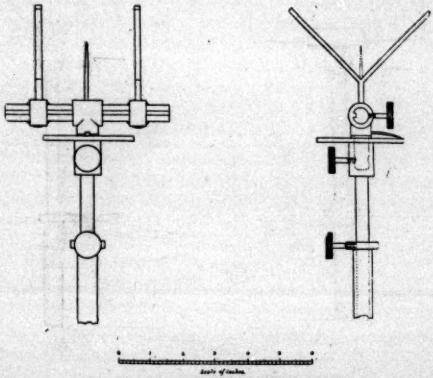


Fig. 8.

concentric circles, the lens is then focused in the ordinary way and the screen traversed horizontally or vertically, or both, until the focus is brought in the centre of the field. The readings on the two scales give the amount of decentering at once. These arrangements are indicated in the drawing fig. 8.

(2) Determination of the Principal or Equivalent Focal Length.

This has been sufficiently described before.

(3) Determination of the Aperture.

The angular aperture of any lens combination can of course easily be ascertained with the aid of the lens holder before described, if a

scale of degrees is provided on the vertical axis. The lens is mounted for testing in the ordinary way, or rather should be already in adjustment from the previous test, and is turned about the vertical axis until the light appears to be all cut off in the telescope, or the stop begins to disappear, etc. In this way the apertures of the extreme cone, and of the cone for which the stop is entirely visible can be very readily determined. The effective aperture of the stops can either be obtained by direct measurement of their diameter, and calculation or by the Kew test which can be modified to suit the apparatus.

(4) Measurement of the Chromatic Aberration.

Here again the procedure is obvious, for ordinary tests the collimator may simply have a piece of red and of blue glass interposed successively between it and the light, and the variation in focal length be noted in the same way as in the well known Kew test. For more accurate work if the apparatus is on a sufficiently accurate scale to warrant it, light may be thrown on the aperture by means of a spectroscope and any suitable wave length chosen.

(5) Measurement of the Spherical Aberration.

For this purpose the focal lengths can simply be determined when annular diaphragms of different diameters are placed in front of the lens to be tested, it is generally sufficient to adopt the ordinary procedure of the disc and ring stops, but the amount of spherical aberration for any particular zone can be obtained if desired.

(6) Measurement of the Distortion.

The lens being in position, the distortion is at once obtained by the simple method used by M. Möessard, the nodal point of the combination being on the axis as was arranged in testing the focal length. The lens is rotated on the vertical axis for angles of 10°, 20° 30°, etc., the displacement of the image is the measurement of distortion in each case, and can be measured directly if required by a micrometer in the field of the telescope eyepiece.

(7) Measurement of the Astigmatism.

If the lens is astigmatic it of course brings the light when obliquely placed to two focal lines as in the case of a sphero-cylinder, and the distance between these lines is usually taken as the measure of the astigmatism. The lens is therefore simply set to any inclination of the

axis as in the last case, and the distance between the focal lines determined as if the lens were a sphero-cylinder.

(8) Measurement of its Focal Volume and Curvature of the Field.

The focal volume implies the space within which the image of a point is not greater than a specific standard usually taken as 1/100th of an inch. In order to determine this volume the collimator is provided with an aperture so small as to be practically a luminous point, and the lens being set at various angles, the distance through which it can be moved without the image extending to a greater size than that mentioned can be at once read off on the telescope if a suitable micrometer or diaphragm is employed. The focal volume can then be plotted out on a sheet of suitably ruled paper in the ordinary manner.

The procedure followed in these tests is almost identical with that adopted by M. Möessard in connection with his well known tourniquet. They have been very briefly mentioned here merely to show that the arrangement if made on a suitable scale is adaptable for such tests.

SENSITIVENESS OF THE METHOD.

A word should be said before concluding this paper as to the degree of accuracy which can be expected of this method. It will be seen that this depends considerably upon the aperture and optical perfection of the telescopes employed, as the amount of error simply depends on the depth of focus of the telescope. With fairly ordinary achromatic glasses of about 2½″ to 3″ aperture of object glass the depth of focus is something of the order of 2 or 3 mm. It will therefore be seen that although the method is fairly accurate for lenses of moderately long focal length, it would not be particularly so for short focus lenses. Of course this is a difficulty which arises in all matters of optical testing, as the range to be used is so great. For short focus lenses the apparatus might either be made on a smaller scale if desired (a similar arrangement is being devised for testing microscope objectives), but short focus lenses can be measured with any higher degree of accuracy if necessary by employing an auxiliary lens between the lens tested and the telescope. If the telescope, for instance, is adjusted for parallel rays and the lens to be tested has its surface focused by means of the auxiliary lens, it may be of as short focus as may be wished. The test can be proceeded with in exactly the usual way, and will be much more sensitive. There should, however, be no difficulty in obtaining object glasses which should give results accurately to half a millimeter.

A familiarity with the use of the apparatus soon enables one to perform lens testing with any ordinary degree of accuracy. It would no doubt have been preferable for some tests if a Barr and Stroud range finder had been substituted for the observing telescope, and indeed for the collimator. This is a much more sensitive instrument than a telescope, but its use would detract from the universality of the instrument when dealing with cylindrical or sphero-cylindrical lenses, and even for spherical lenses of very different apertures. On the whole then it has been considered advisable to retain the ordinary telescope although at some cost of sensitiveness.

(*Added 18/2/01.*) It would seem necessary to allude to the effect of the accommodation of the eye on the accuracy of reading. Of course, no error in the refraction of the observer's eye is of importance, as the same error is made in focusing both the lens surface and the image. As far as the accommodation of the eye is concerned its effect can be greatly lessened by using a high power eyepiece in the telescope, or for greater accuracy a disc having two apertures may be used in the path of the light. This eliminates accommodation almost completely.

In conclusion the attention is called of those who may require a considerable amount of rapid lens testing to the simple arrangement which is used for moving the lens stand. Two pulleys are attached to the supports of the collimating and observing telescopes, over which an endless cord runs attached to the lens stand, a single observer at the telescope can then adjust the position of the lens as he pleases. It should also be noted that when testing thin lenses such as ordinary spectacle lenses, it is sufficient once for all to focus the aperture in the screen holding the lenses when at zero. There will then be no need to repeat the focusing on the lens surfaces each time. The rapidity of lens testing carried out in this way is in general very much greater than that of any other method with which the author is acquainted.

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